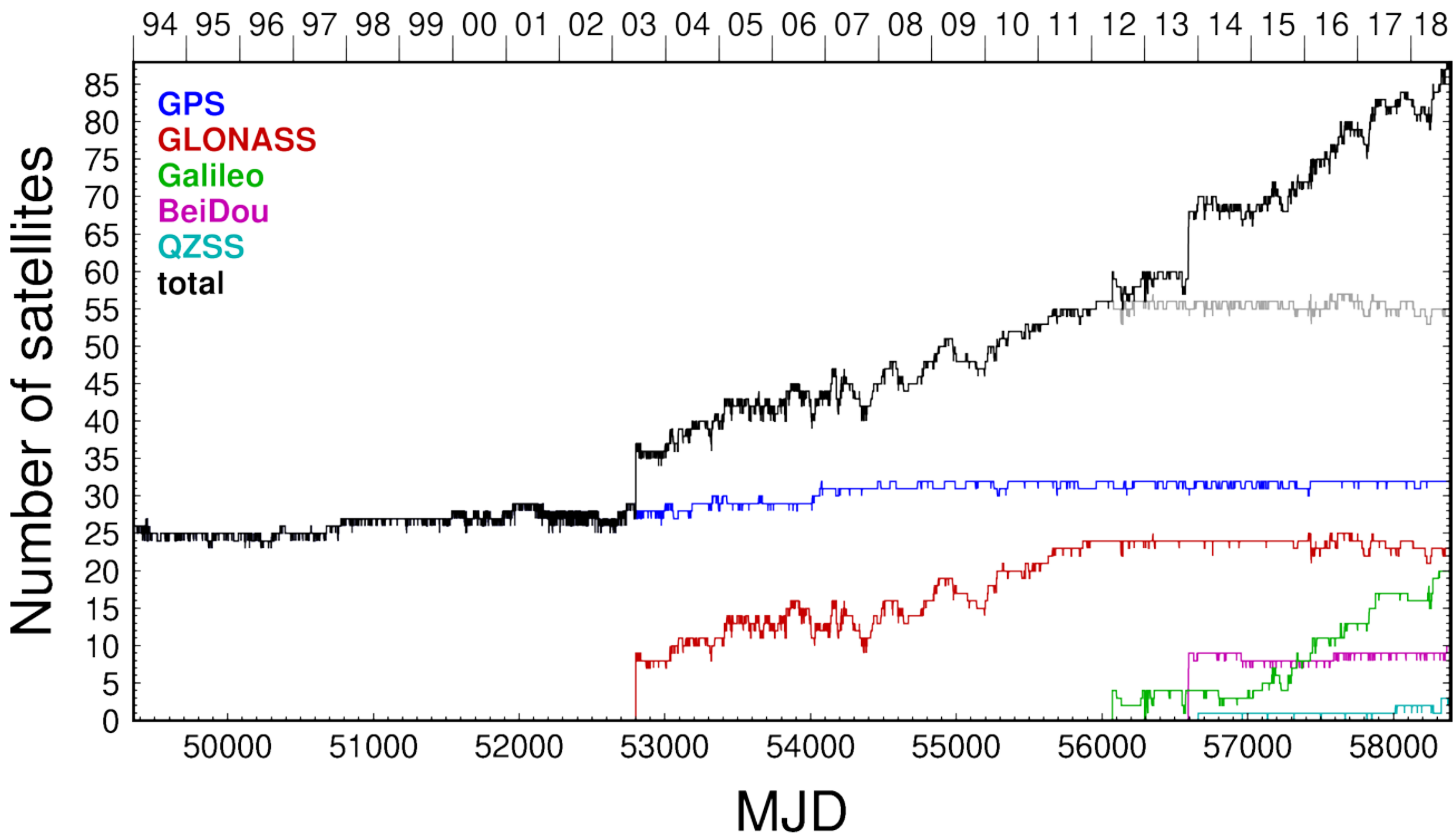
Multi-GNSS: more satellites – more challenges for orbit determination

Rolf Dach, Lars Prange, Dmitry Sidorov, S. Lauren McNair and the CODE AC team

Astronomical Institute, University of Bern

International Symposium on Geodesy & GNSS 2018
Xuzhou China, November 3–4 2018

Number of Satellites in the CODE solutions



Navigation Satellite Systems today

Global Navigation Satellite Systems


GPS


GLONASS

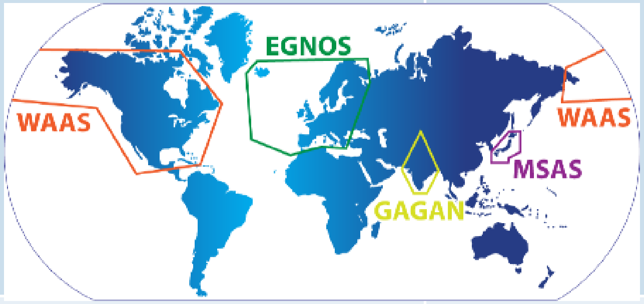

Galileo


BeiDou

Regional and Augmentation Systems


QZSS


NAVIC



SBAS

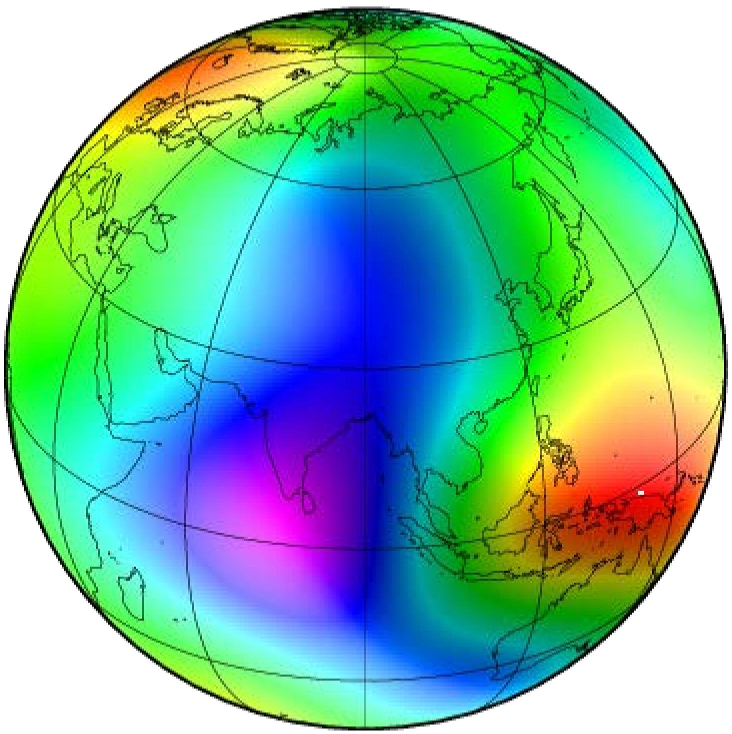
Theoretical background

Equation of Motion applies for all satellites

The shape of a satellite orbit is influenced by

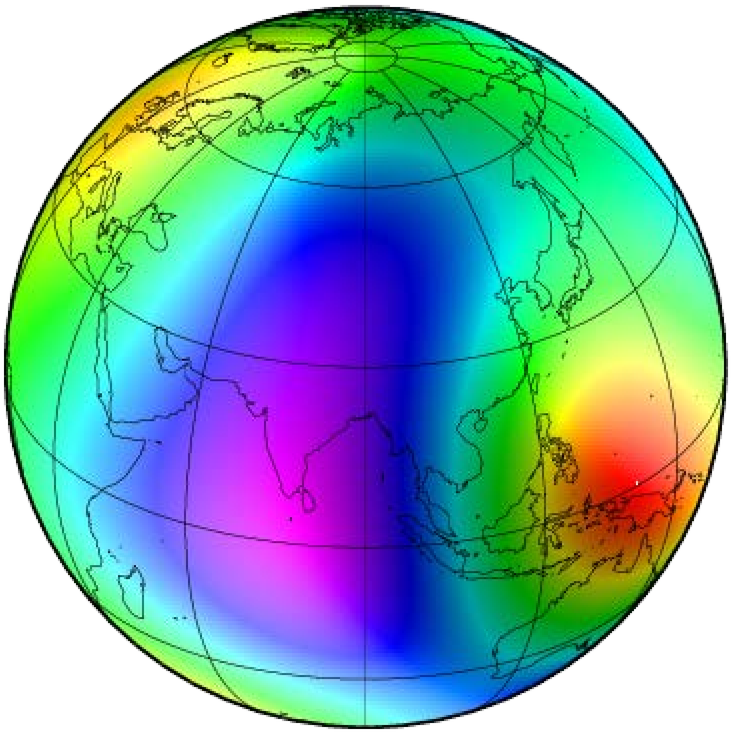
- Keplerian motion
- Gravitational forces
  - Attraction by the Earth and other bodies
  - Mass distribution in/on the Earth
- Non-gravitational forces

Gravitational Forces



- Resolution of the Earth gravity field relevant for modelling the orbits of GNSS satellites in MEO orbits.

Gravitational Forces



- Resolution of the Earth gravity field relevant for modelling the orbits of GNSS satellites in GEO/IGSO orbits.

Gravitational Forces

Relevant gravitational effects for GNSS orbit modelling:

- Oblateness of the Earth
  GPS: ≈40 km Galileo: ≈27 km QZSS: ≈15 km
- Lunar gravitational attraction
  GPS: ≈1.5 km Galileo: ≈3 km QZSS: ≈5 km
- Solar gravitational attraction
  GPS: ≈1 km Galileo: ≈2 km QZSS: ≈6 km
- Earth gravity field (remaining parts)
  GPS: ≈500 m Galileo: ≈300 m QZSS: ≈200 m
- Gravitational effect due to ocean tides
  GPS: <1 cm Galileo: <5 mm QZSS: ≈1 mm

Equation of Motion applies for all satellites

The shape of a satellite orbit is influenced by

- Keplerian motion ✔
- Gravitational forces ✔
  - Attraction by the Earth and other bodies
  - Mass distribution in/on the Earth
- Non-gravitational forces ?
  - Any interaction of radiation with a surface causes an exchange of momentum and therefore a force.
  - Thermal emission also generates a force.

Direct Solar Radiation Pressure

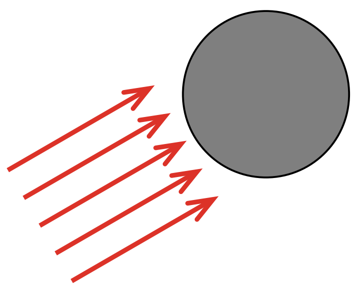
One of the biggest effect on GNSS satellites is the force produced by the photons directly coming from the Sun.

Effect on the satellite orbit after one day:

- GPS satellites: ≈250 m
- Galileo satellites: ≈350 m
  satellites have comparable dimensions but only half of the mass
- QZSS satellites: ≈700 m
  satellite dimensions are much bigger than for the other GNSS satellites

Radiation Effect in the Orbit Determination

We need to know which amount of photons arrives at the satellite. According to the surface properties the resulting force can be derived.

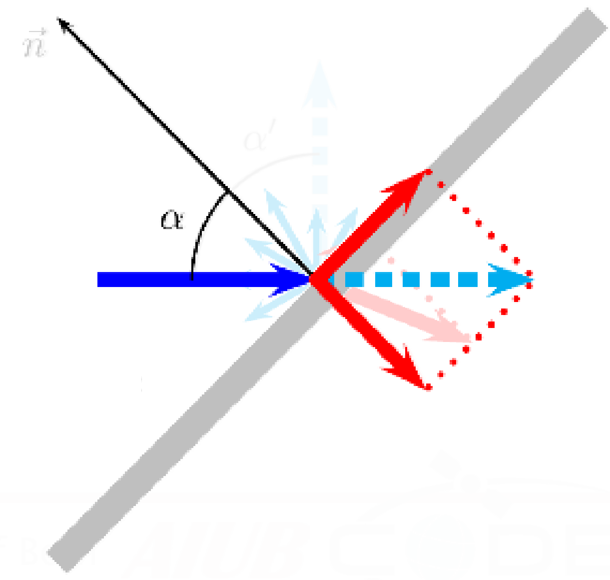


p_s–specular Reflection

p_d–diffuse Reflection

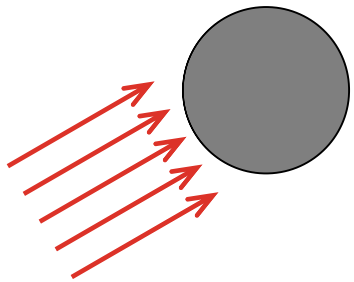
p_a–absorbtion

$$\mathbf{p_s + p_d + p_a = 1}$$



Radiation Effect in the Orbit Determination

We need to know which amount of photons arrives at the satellite. According to the surface properties the resulting force can be derived.



Analytical Modelling

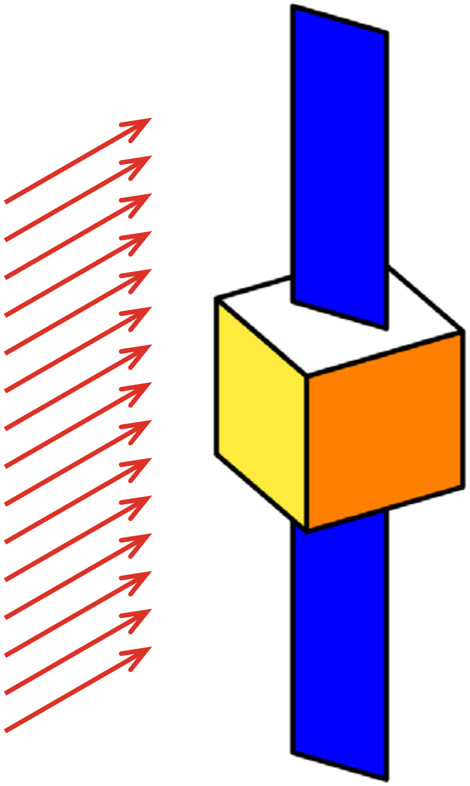
For an analytical modelling of the radiation and re-radiation effects one needs

- a detailed decomposition of the satellite into the geometrical elements,
- the optical properties of all surfaces (including the consequences of aging effects),
- a reasonable knowledge about the radiation arriving at the satellite, and
- sufficient information about the thermal conditions of the satellite surfaces.

With a ray tracing the resulting acceleration can be computed but this needs a big computational effort.

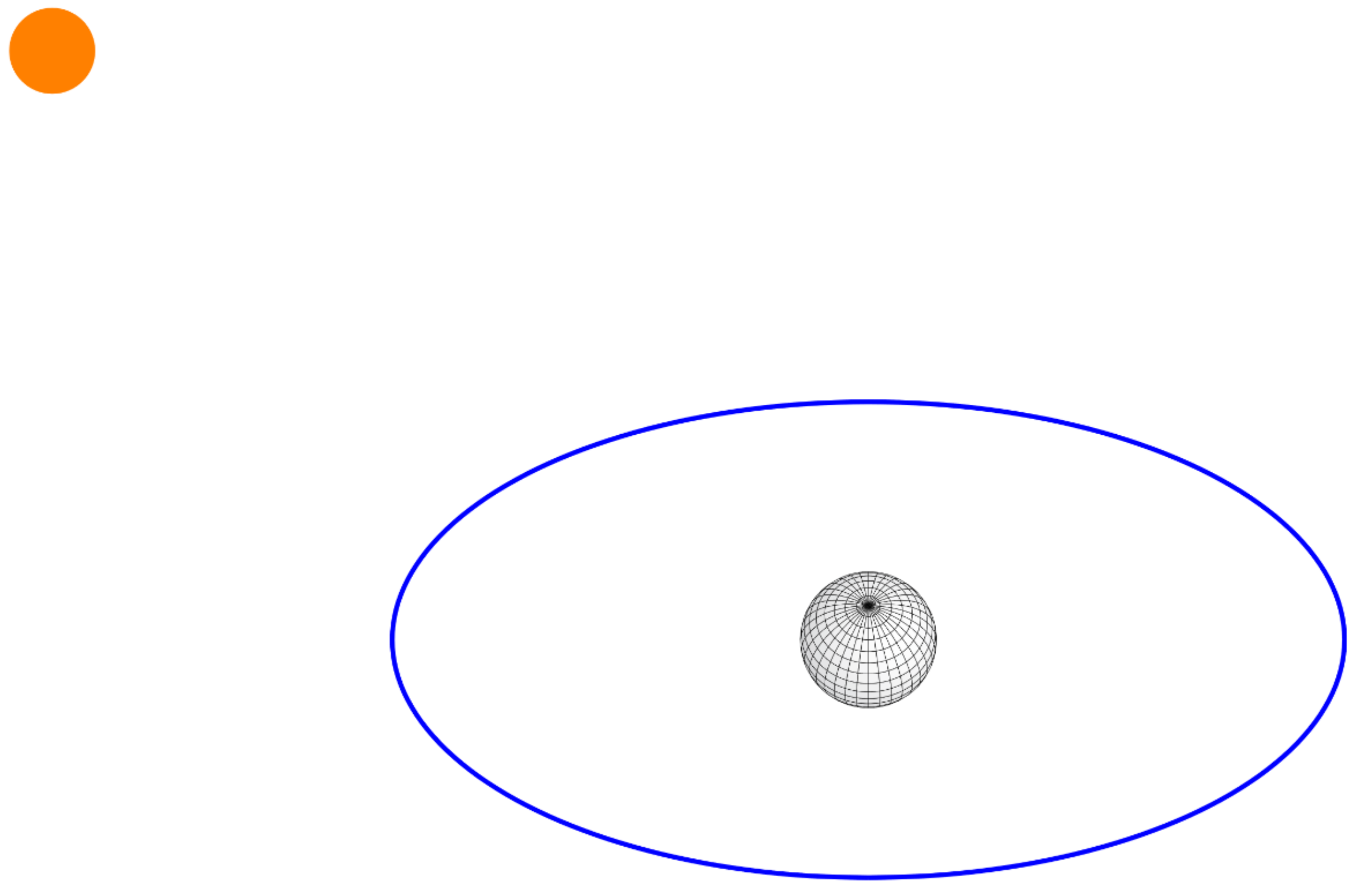
Semi-analytical modelling

To reduce the computational effort, the satellite is typically re-presented by a box-wing model.

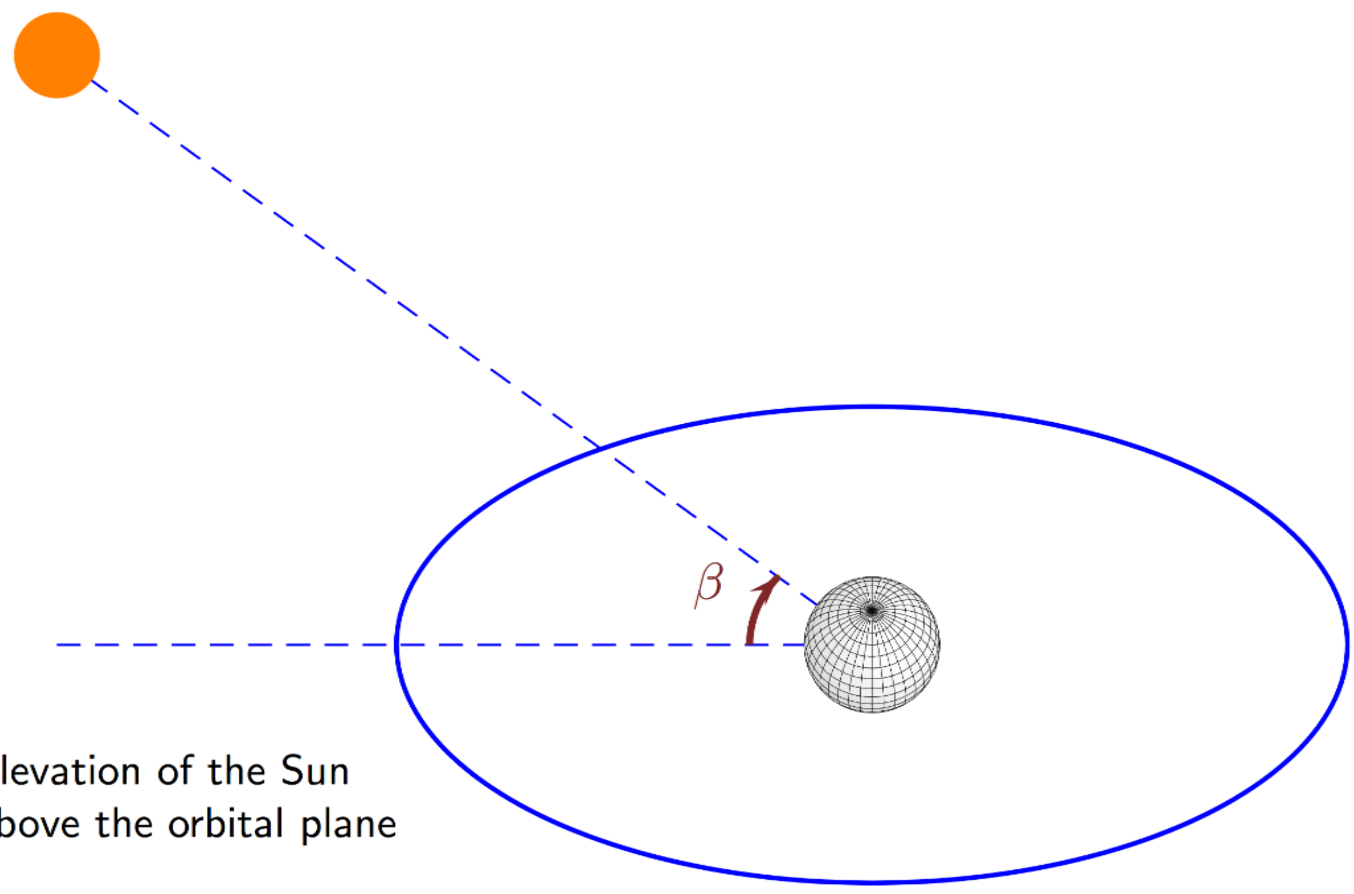


+empirical orbit parameters that need to be estimated

Empirical modelling

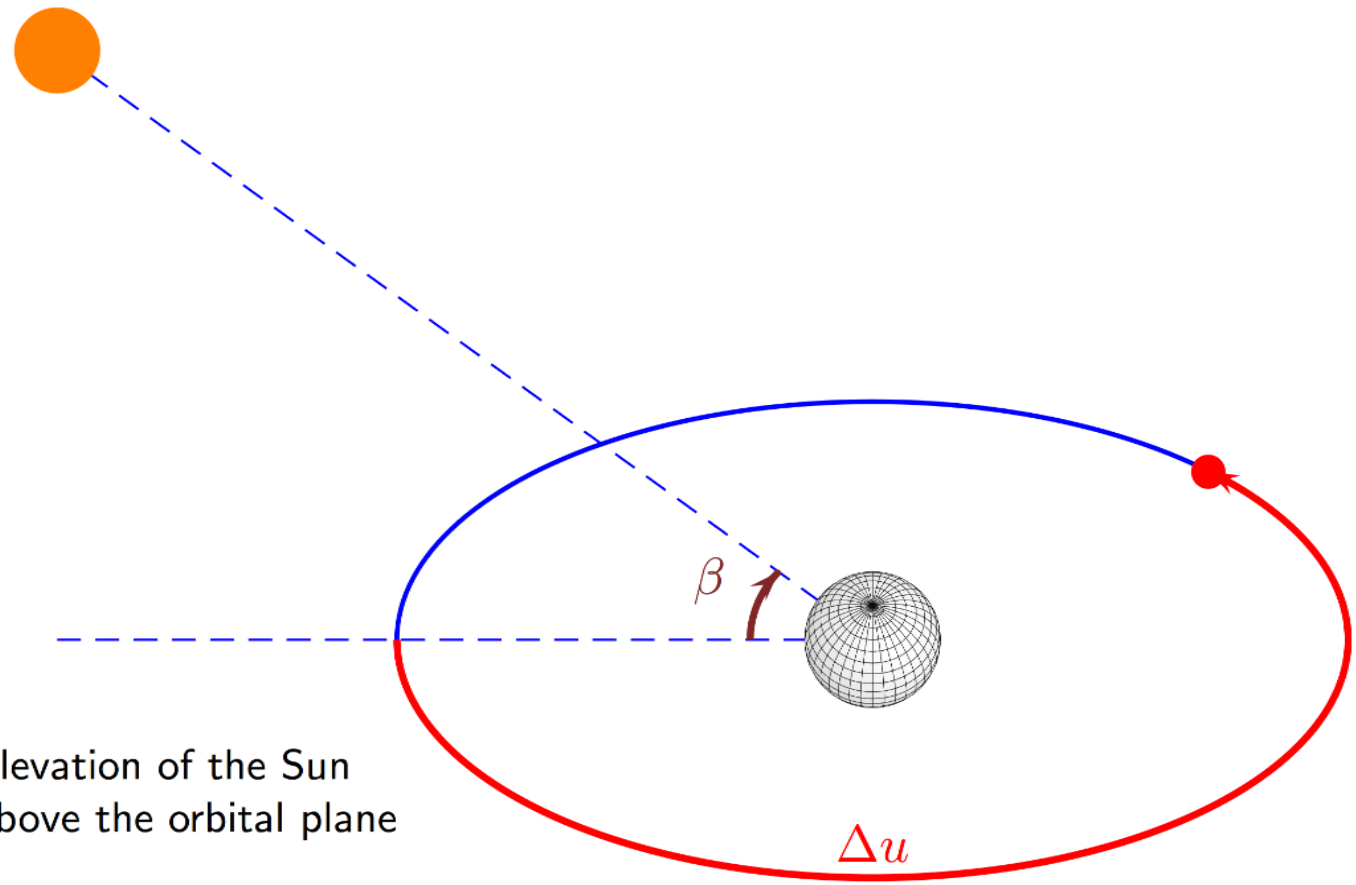


Empirical modelling



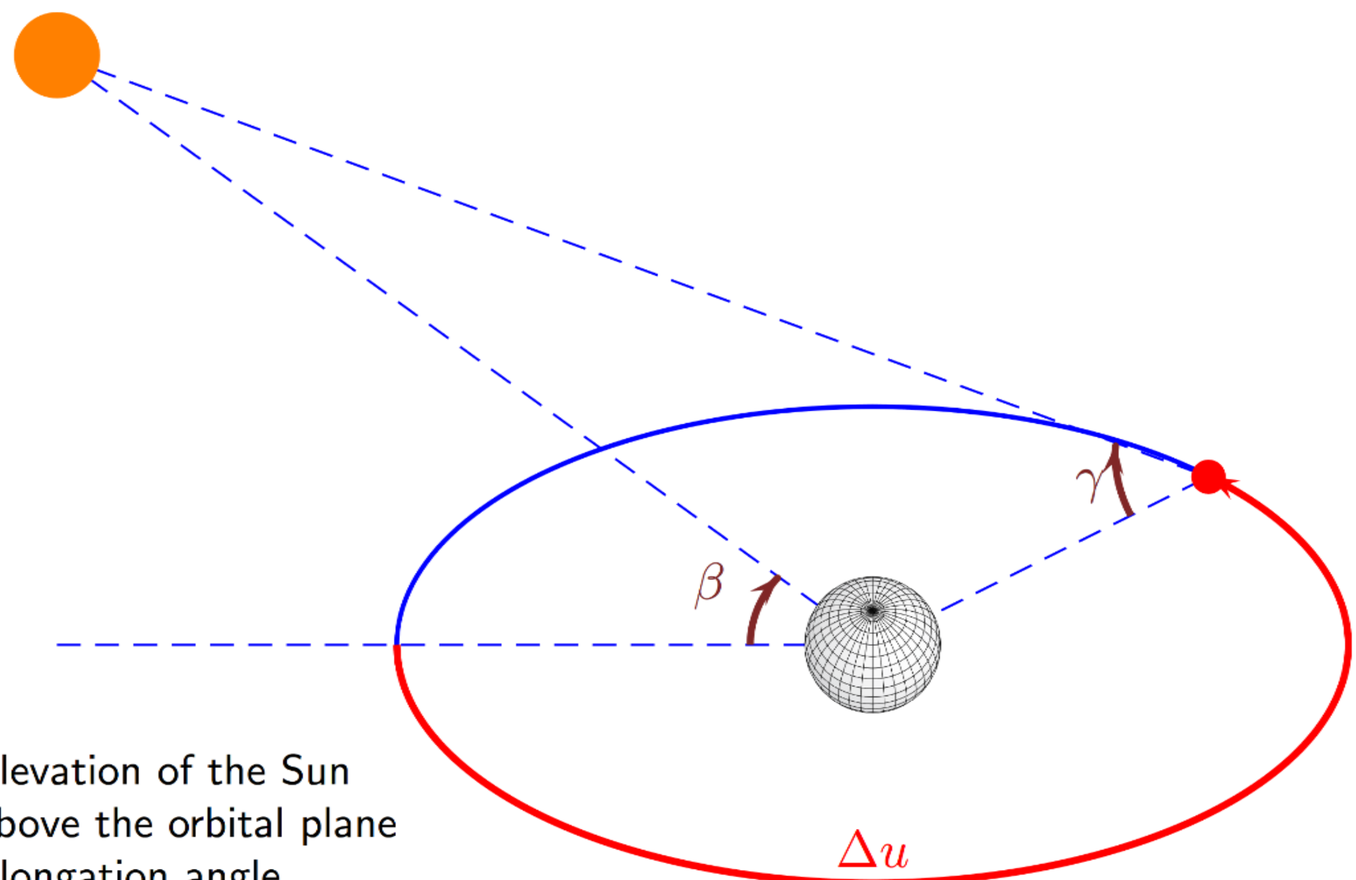
β Elevation of the Sun above the orbital plane

Empirical modelling



β	Elevation of the Sun above the orbital plane
Δu	Difference $u_{sat} - u_{Sun}$

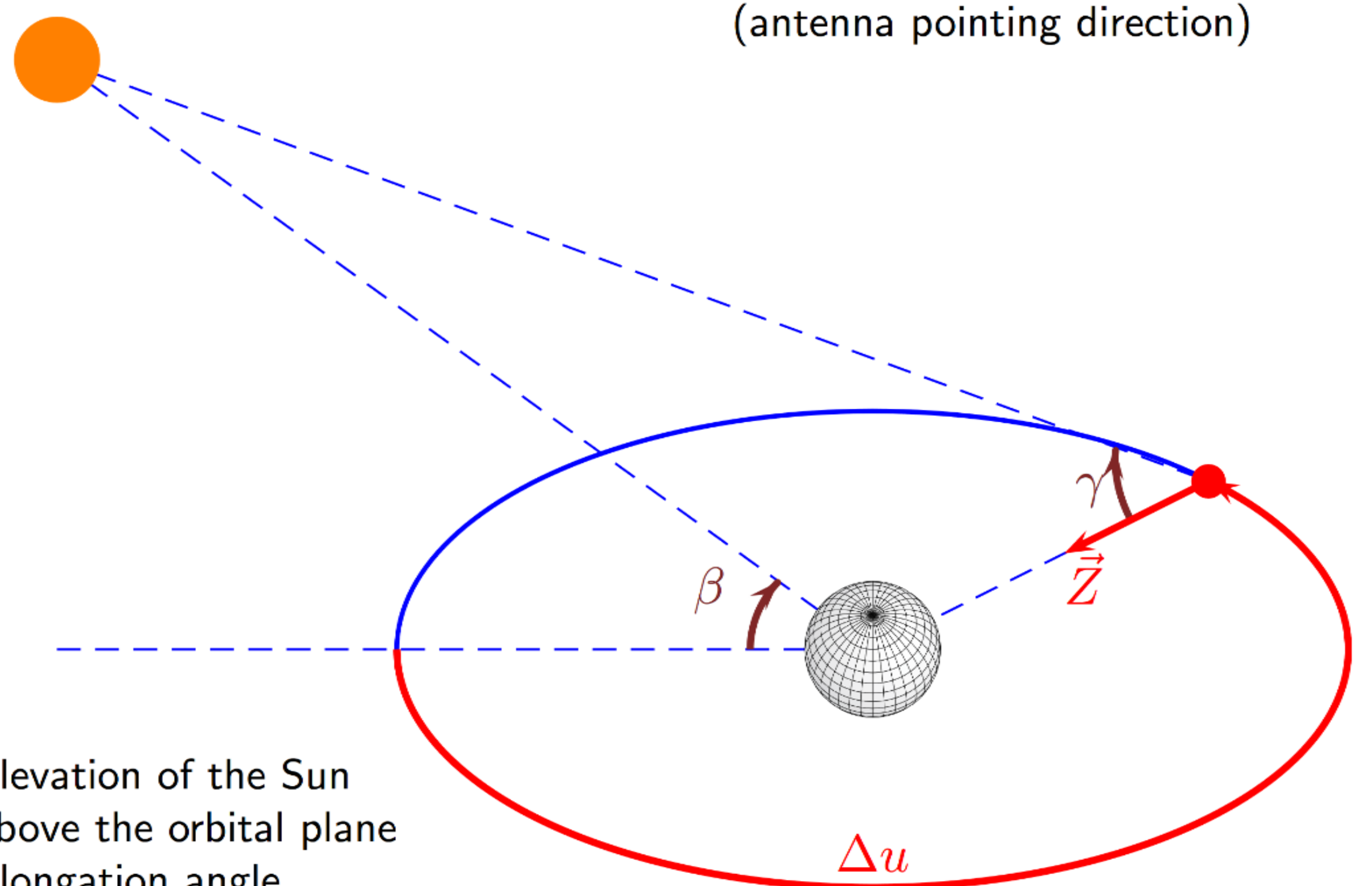
Empirical modelling



β	Elevation of the Sun above the orbital plane
γ	Elongation angle
Δu	Difference $u_{sat} - u_{Sun}$

Empirical modelling

$\vec{Z}$ Direction satellite $\rightarrow$ Earth (antenna pointing direction)



β Elevation of the Sun above the orbital plane

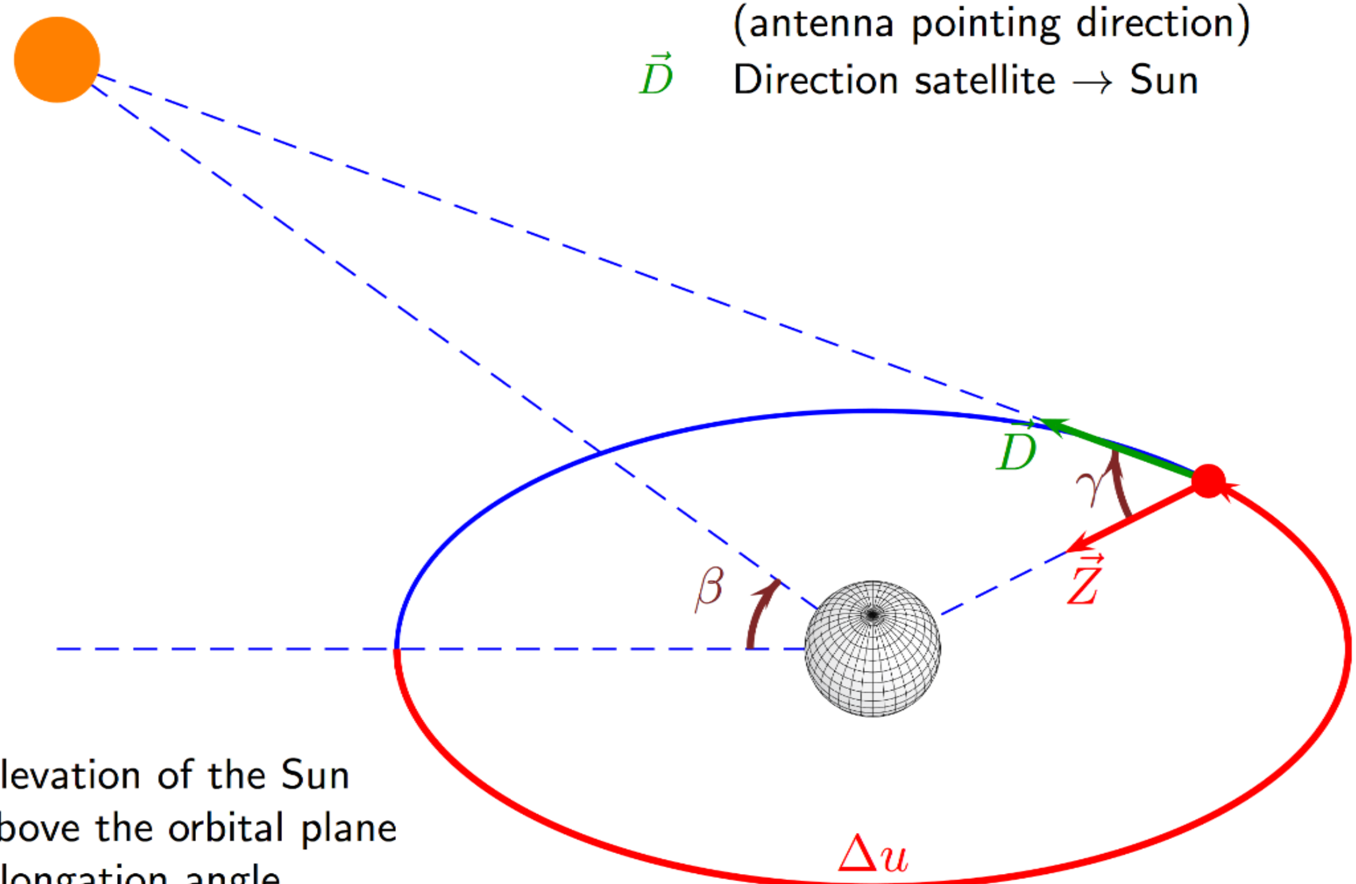
γ Elongation angle

Δu Difference $u_{sat} - u_{Sun}$

Empirical modelling

$\vec{Z}$ Direction satellite $\rightarrow$ Earth (antenna pointing direction)

$\vec{D}$ Direction satellite $\rightarrow$ Sun



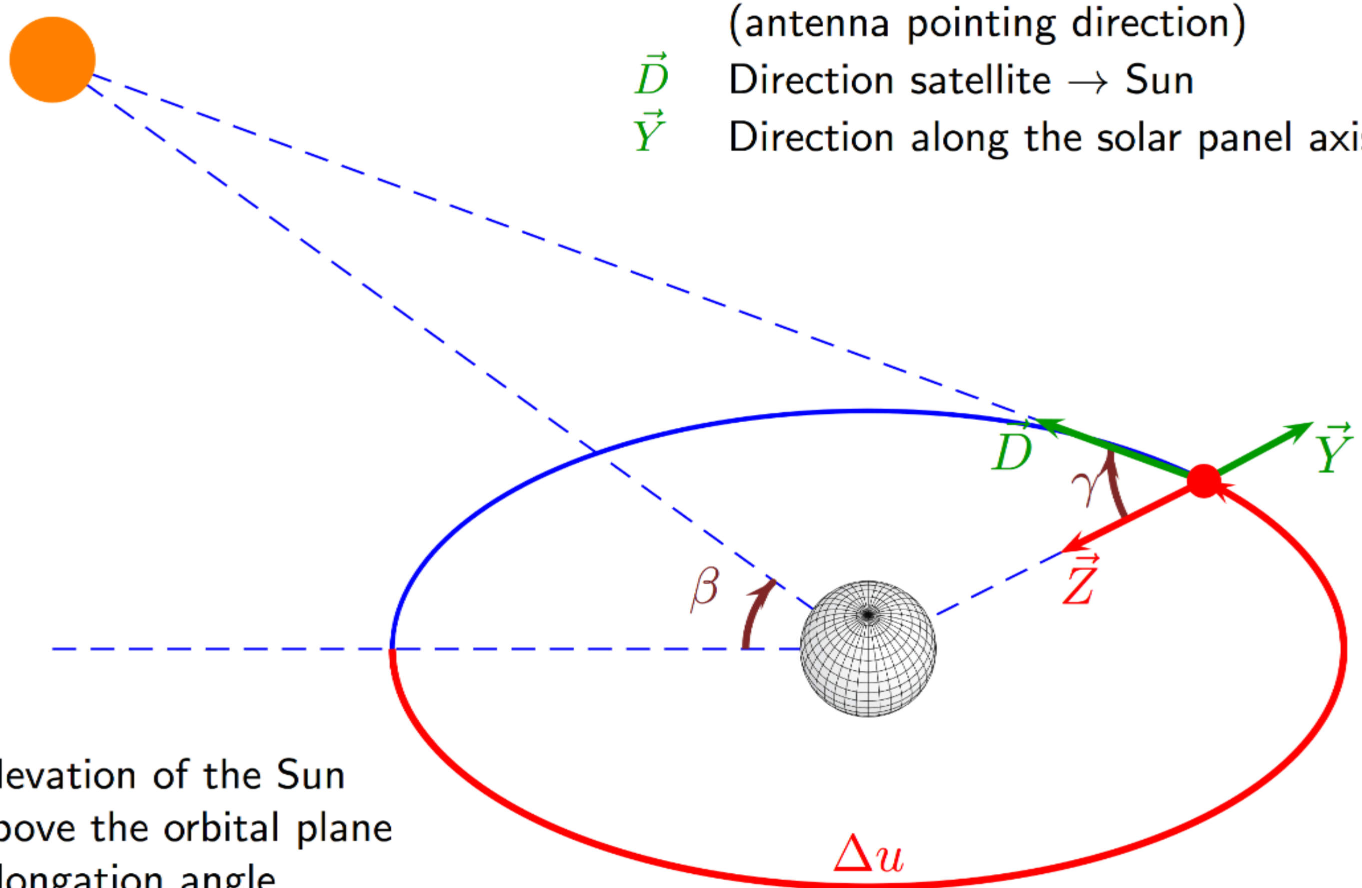
β Elevation of the Sun above the orbital plane

γ Elongation angle

Δu Difference $u_{sat} - u_{Sun}$

Empirical modelling

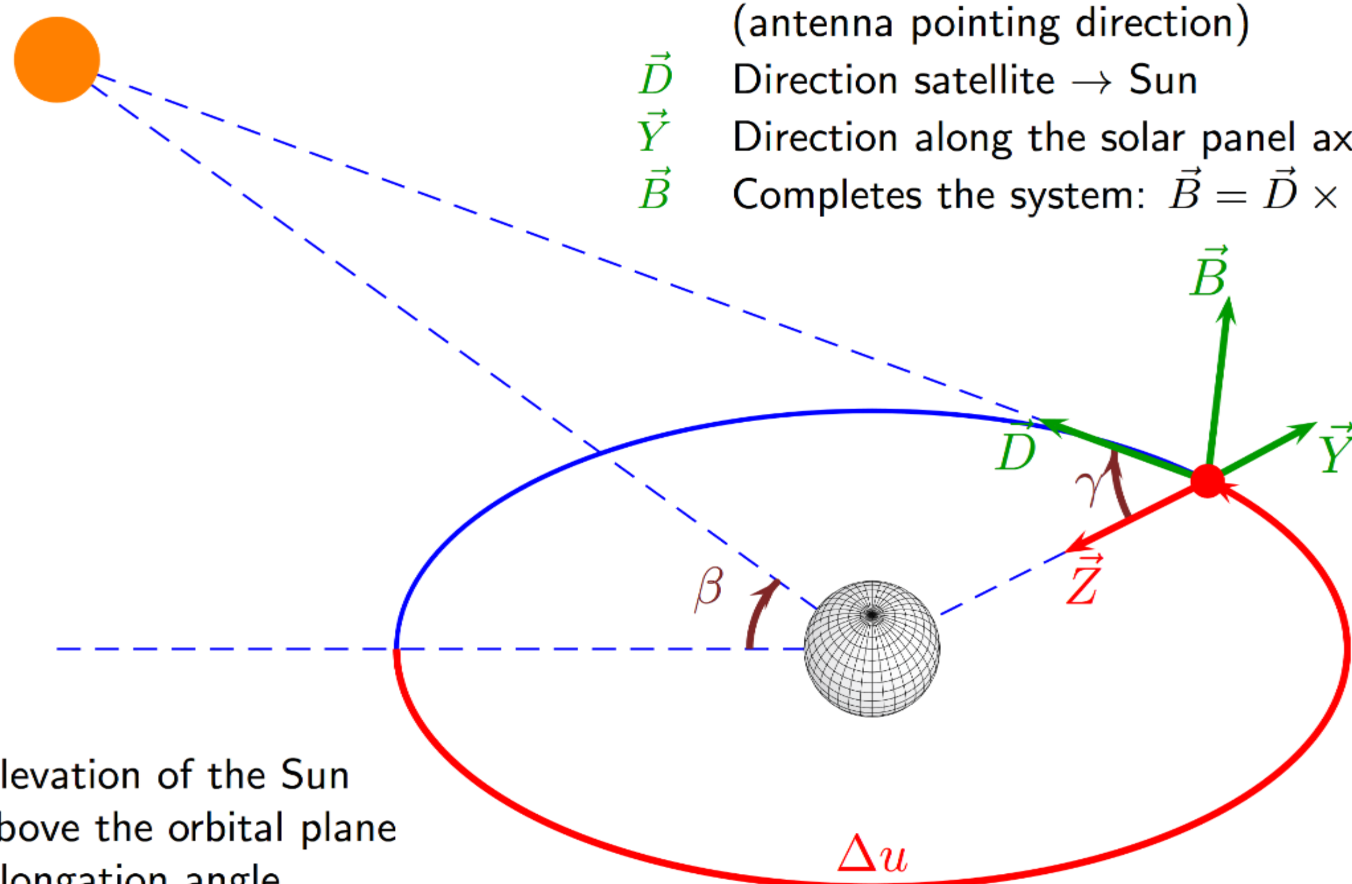
$\vec{Z}$	Direction satellite $\rightarrow$ Earth (antenna pointing direction)
$\vec{D}$	Direction satellite $\rightarrow$ Sun
$\vec{Y}$	Direction along the solar panel axis



β	Elevation of the Sun above the orbital plane
γ	Elongation angle
Δu	Difference $u_{sat} - u_{Sun}$

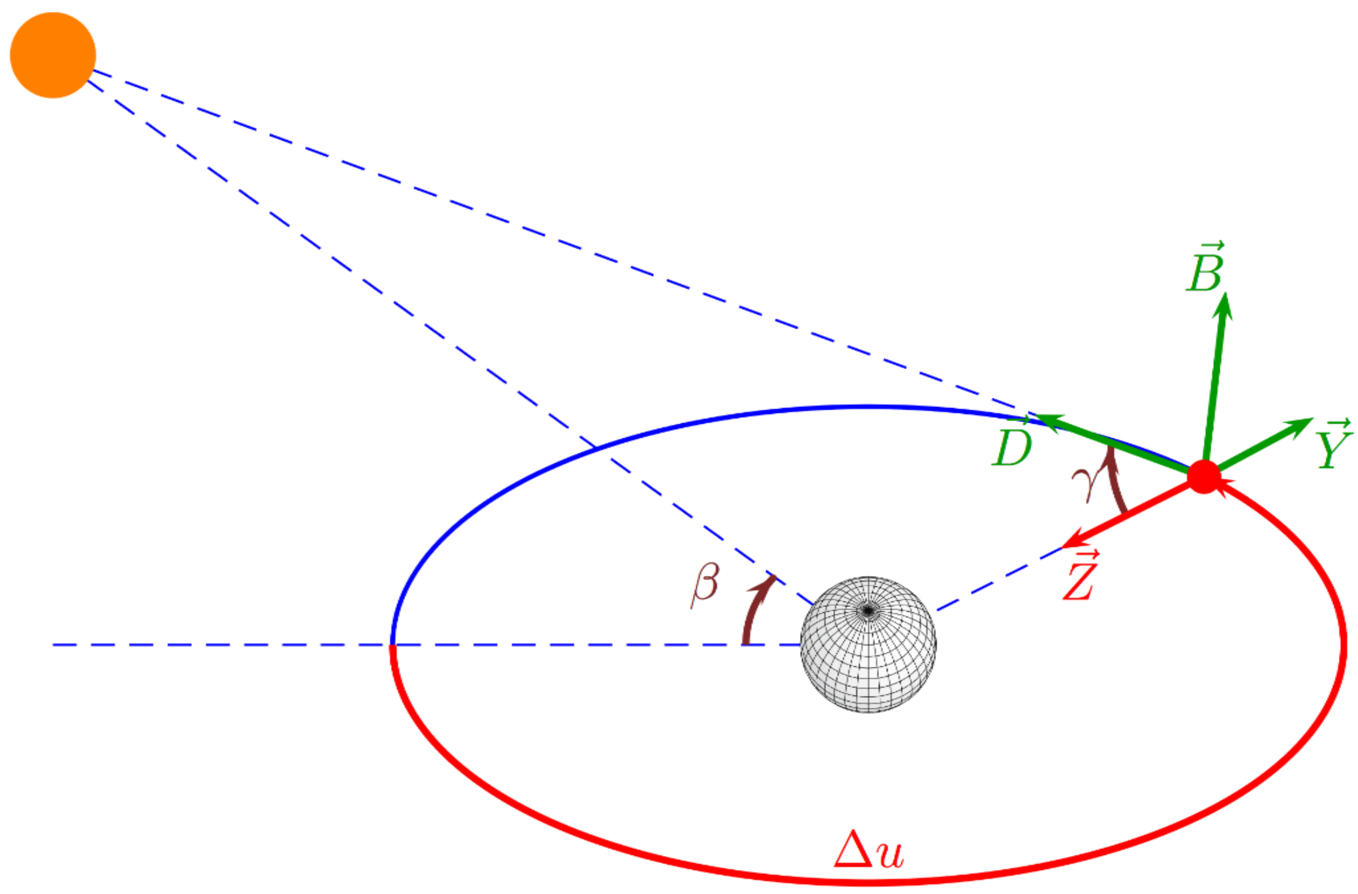
Empirical modelling

$\vec{Z}$	Direction satellite $\rightarrow$ Earth (antenna pointing direction)
$\vec{D}$	Direction satellite $\rightarrow$ Sun
$\vec{Y}$	Direction along the solar panel axis
$\vec{B}$	Completes the system: $\vec{B} = \vec{D} \times \vec{Y}$

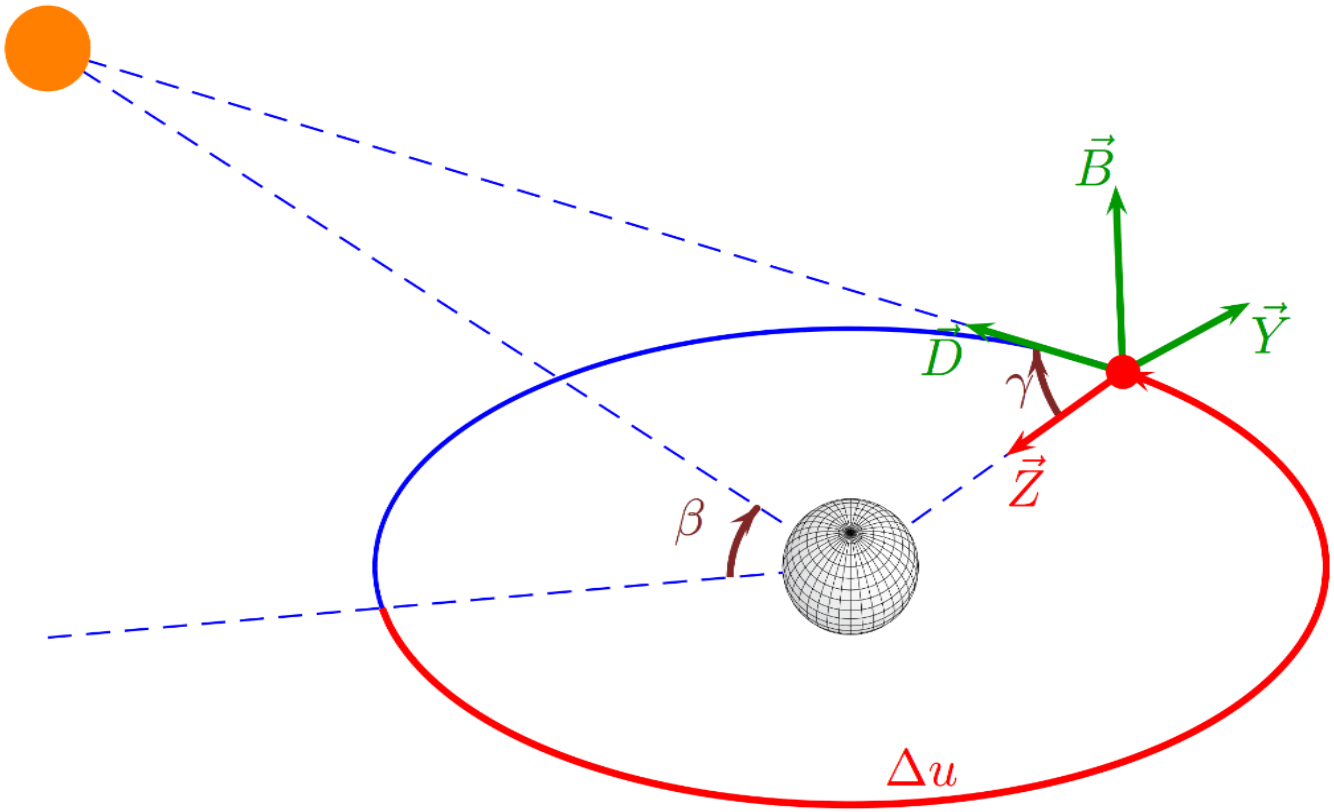


β	Elevation of the Sun above the orbital plane
γ	Elongation angle
Δu	Difference $u_{sat} - u_{Sun}$

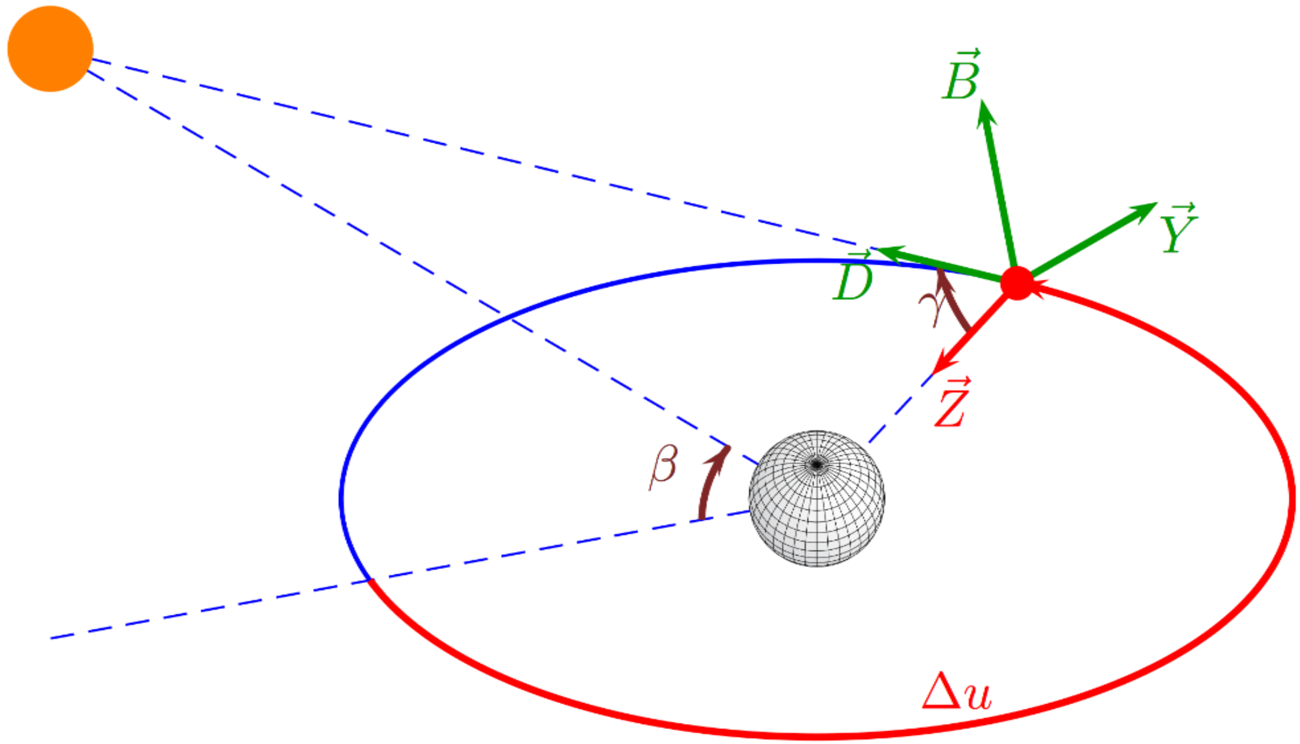
Empirical modelling



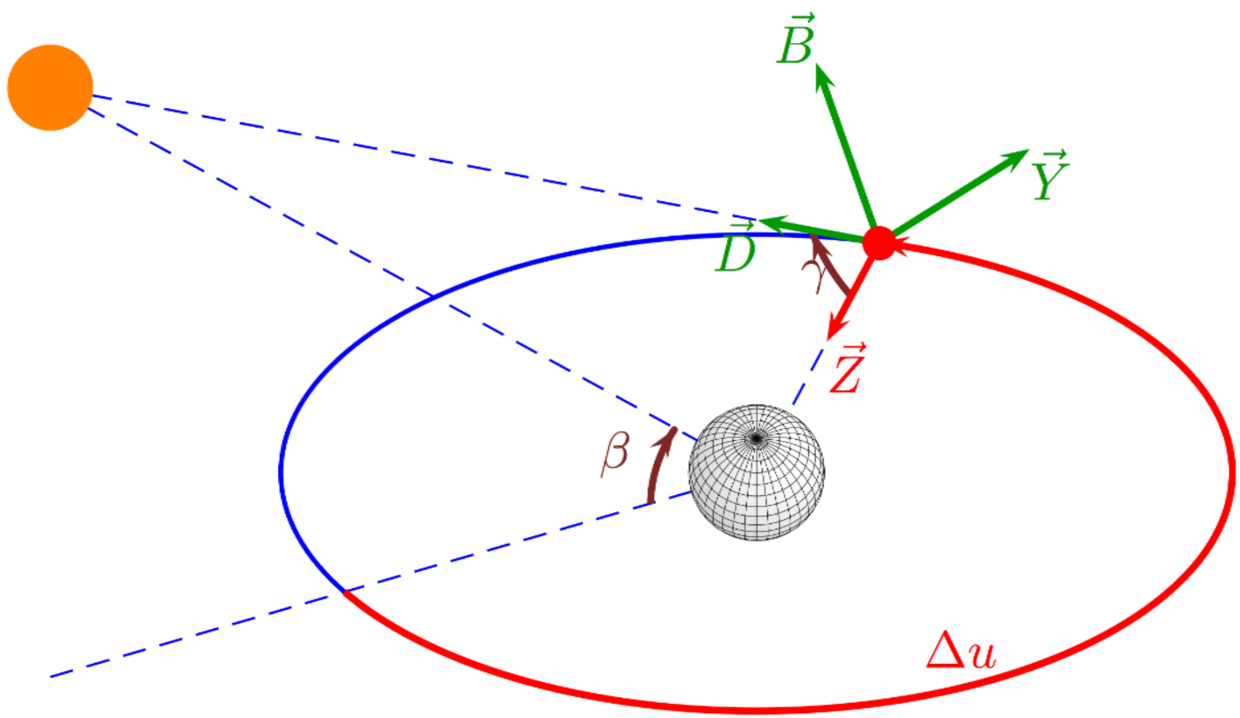
Empirical modelling



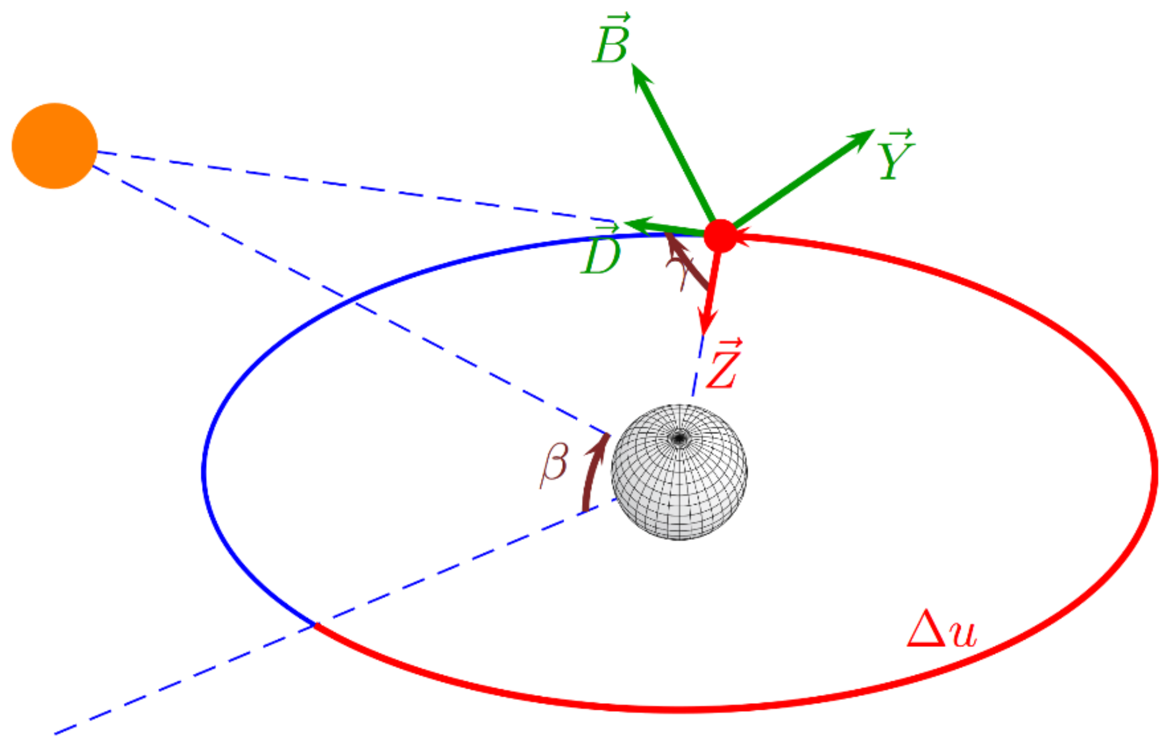
Empirical modelling



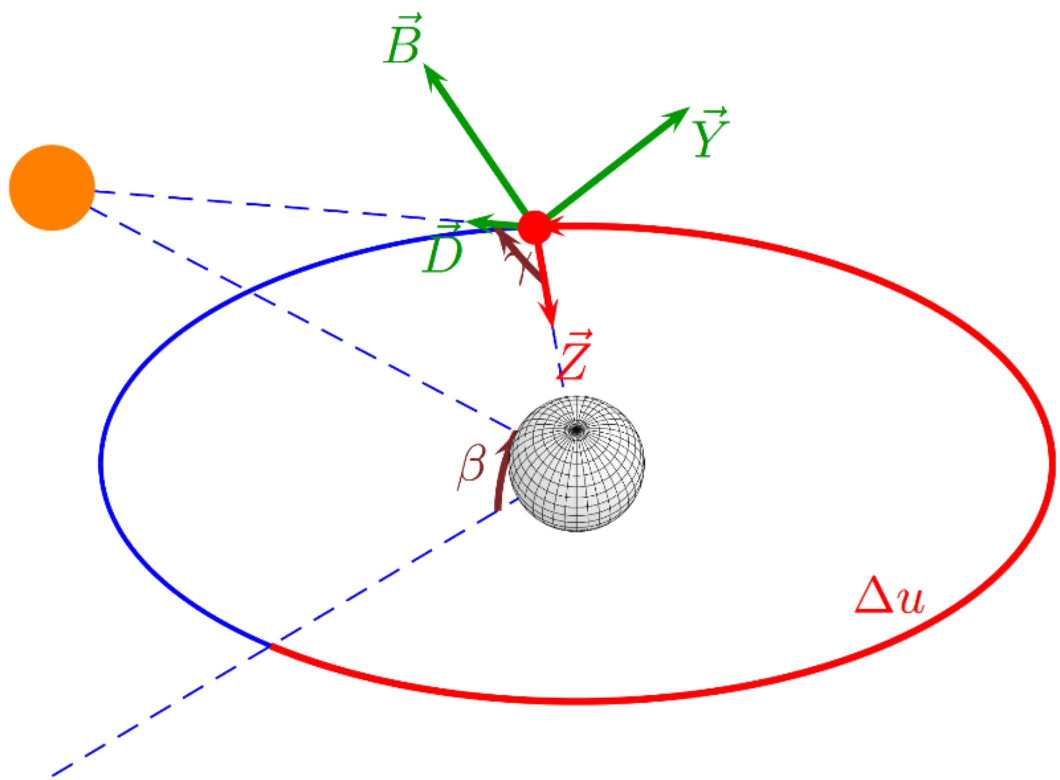
Empirical modelling



Empirical modelling

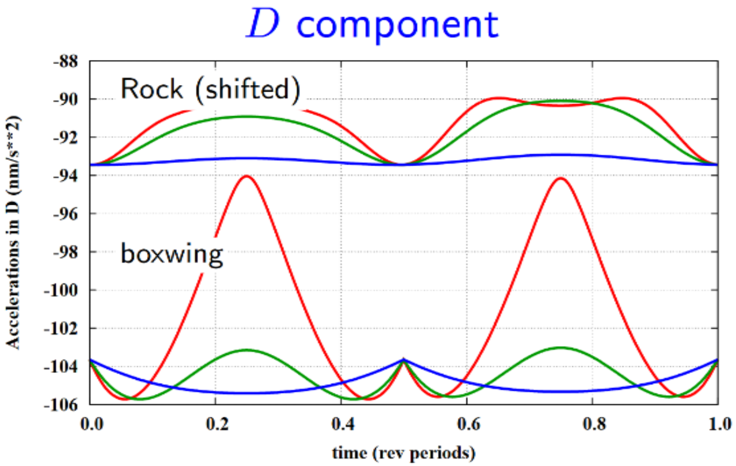


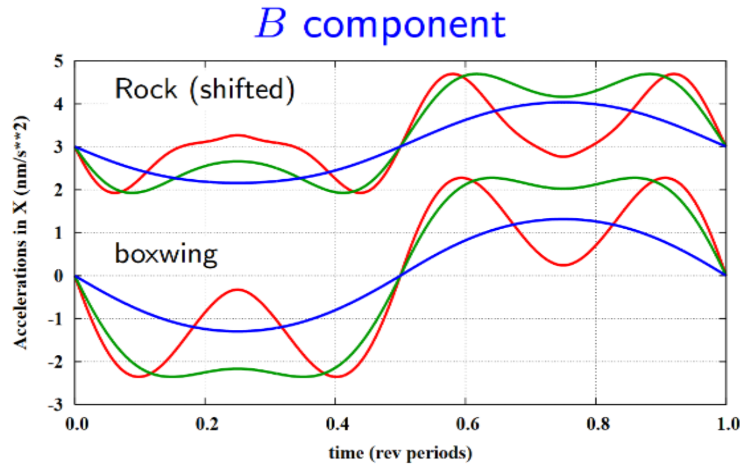
Empirical modelling



Empirical modelling

Accelerations derived for GPS (Block IIA) satellites from a boxwing[1] and Rock-S[2] model





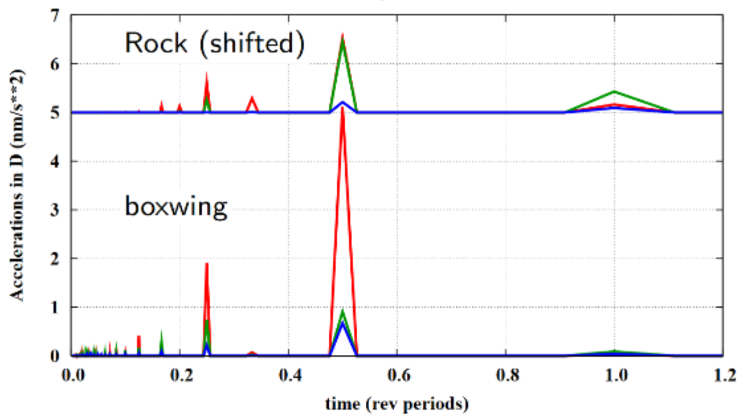
Computed for $\beta = 10°$ $\beta = 45°$ $\beta = 78°$

[1] as proposed by Carlos Rodriguez–Solano based on Fliegel et al. (1992)
[2] Fliegel et al. (1992)

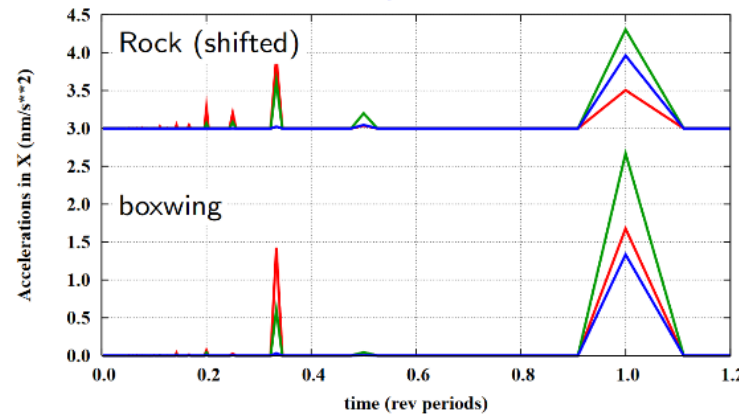
Empirical modelling

Accelerations derived for GPS (Block IIA) satellites from a boxwing[1] and Rock-S[2] model

D component



B component



Computed for $\beta = 10°$ $\beta = 45°$ $\beta = 78°$

[1] as proposed by Carlos Rodriguez–Solano based on Fliegel et al. (1992)
[2] Fliegel et al. (1992)

The Empirical CODE orbit model

The ECOM is well established for GNSS satellites in yaw–steering mode

- A Sun–fixed argument for the periodic terms is helpful to obtain interpretable series of these parameters:

$$\Delta u = u_{sat} - u_{Sun}$$

- Solar radiation pressure for satellites flying according to the previously mentioned models can be represented by:

$$\begin{aligned} D &= D_0 + D_2 \cos(2\Delta u) + D_4 \cos(4\Delta u) + \dots \\ Y &= Y_0 \\ B &= \qquad B_1 \cos(1\Delta u) + B_3 \cos(3\Delta u) + \dots \end{aligned}$$

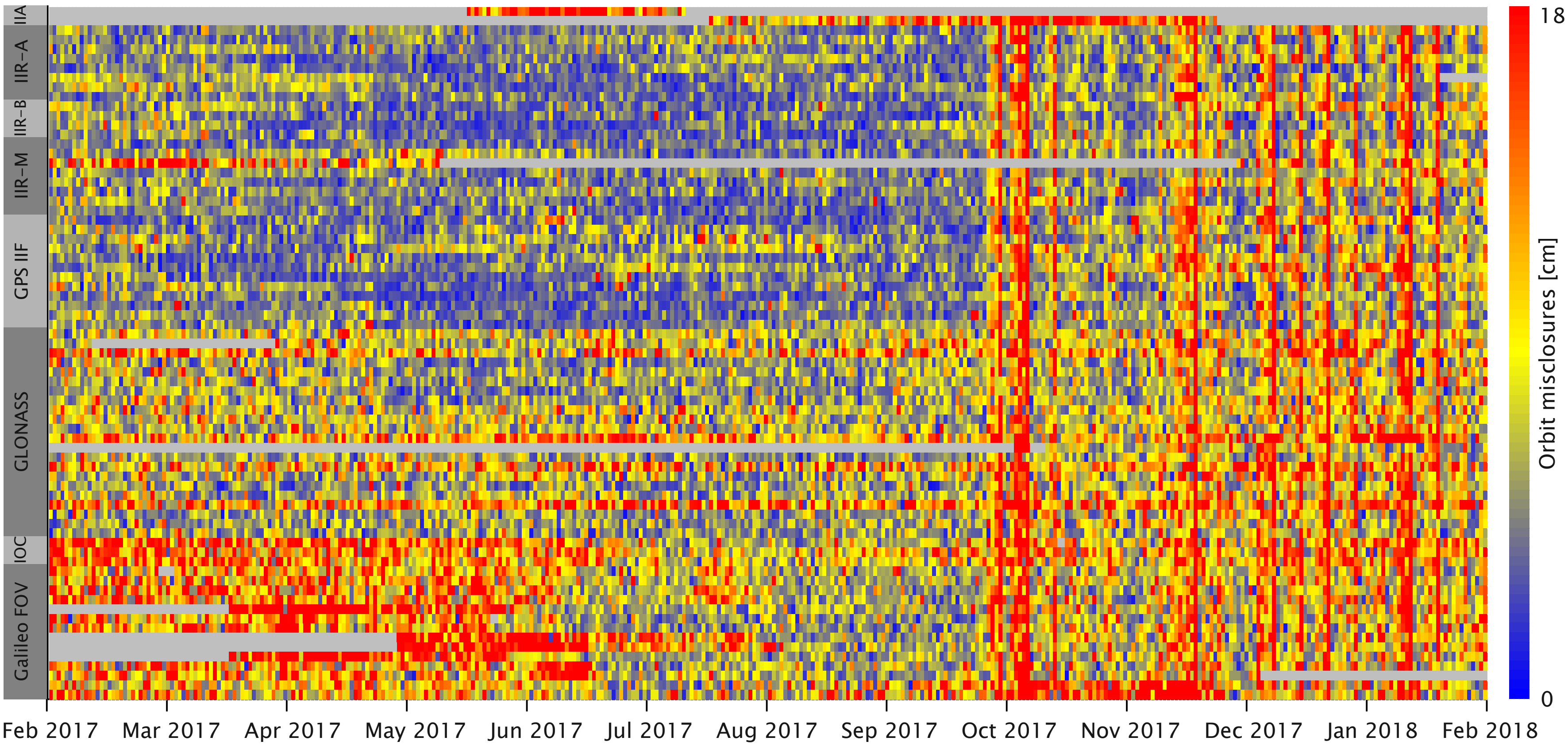
$Y_0 \neq 0$ if the satellite is flying "misaligned" with a Y–bias (e.g., GPS, except for Block IIF).

Scaling factors for box-wing models

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Orbit Misclosures: ECOM-only

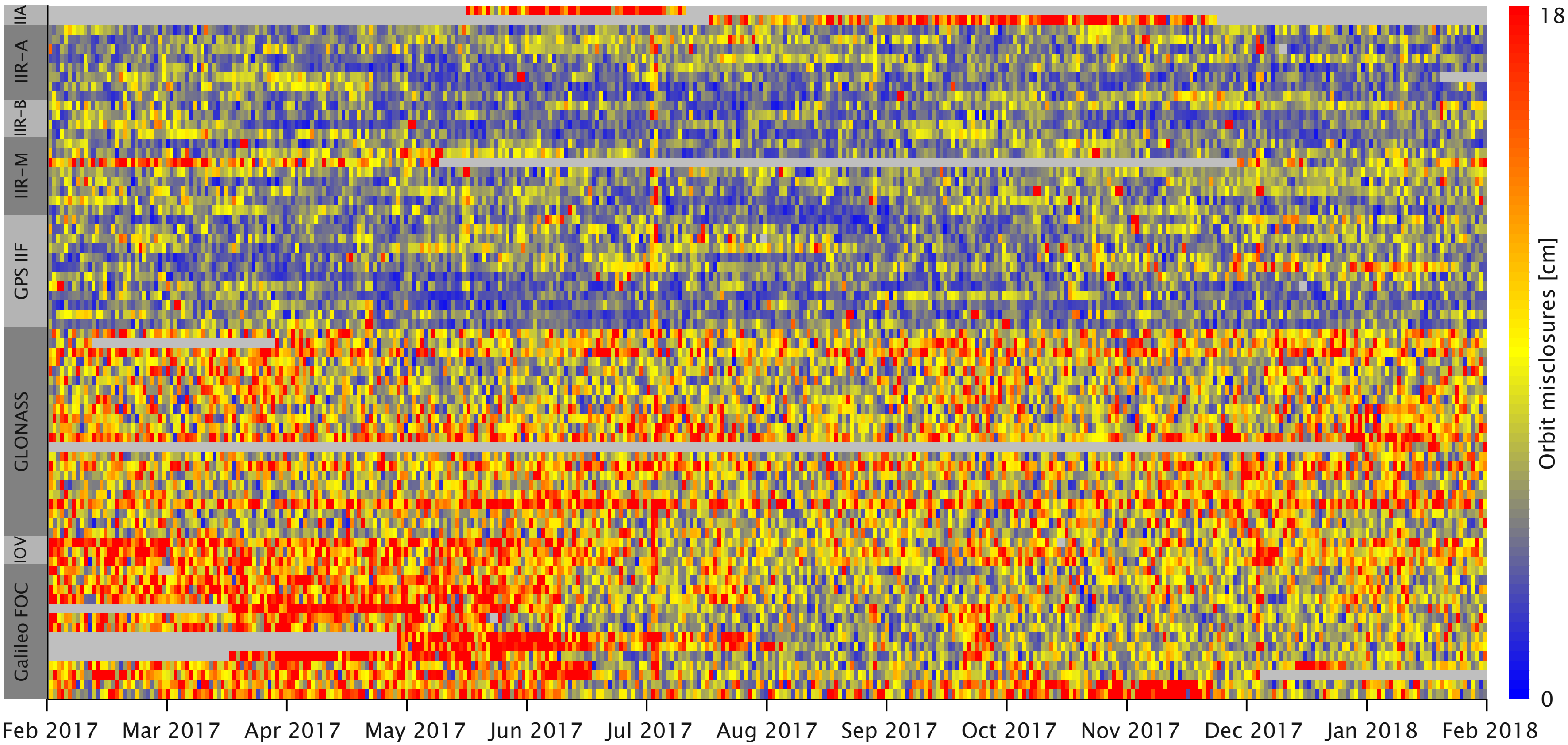
One-day solutions: Galileo has less than two revolutions within one day



L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orbit Misclosures: ECOM-plus-boxwing

One-day solutions: Galileo has less than two revolutions within one day



L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

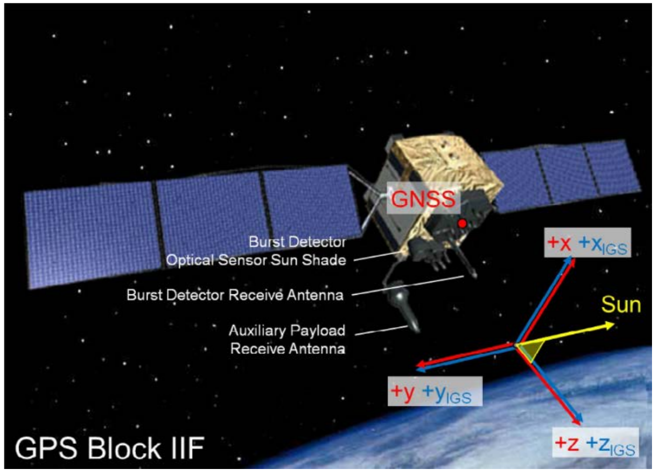
Validate boxwing model

Macromodel defines:

- Plates of the satellite with its areas and surface properties

Used to compute forces acting on the satellite because of solar radiation pressure.

Whether these models are correct can be assessed by estimating scale factors for the resulting force:



[Montenbruck et al, 2015. Adv. In Space Research]

Plate	Mod	Area (A) [m²]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
2	1	5.720	[−1, 0, 0]	0.112	0.448		−X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, −1, 0]	0.112	0.448		−Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
6	1	5.400	[0, 0, −1]	0.000	0.000		−Z
7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0,+1, 0]	Solar panels front
8	0	22.250	[−1, 0, 0]	0.196	0.034	−SUN: [0,+1, 0]	Solar panels back

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Calculating the SRP-Force

Radiation Pressure force calculation per plate:

1. **Without immediate thermal re-radiation:**
   (needed if energy is absorbed, e.g., the solar panel is taking energy)

$$\vec{F} = -\frac{\Phi}{c} \cdot A\cos\theta \cdot \left[(\alpha + \delta)\vec{e}_{\odot} + \frac{2}{3}\delta\vec{e}_n + 2\rho\cos\theta \cdot \vec{e}_n \right]$$

2. **With immediate thermal re-radiation (e.g., for Multi-layer insulation):**

$$\vec{F} = -\frac{\Phi}{c} \cdot A\cos\theta \cdot \left[(\alpha + \delta)\left(\vec{e}_{\odot} + \frac{2}{3}\vec{e}_n \right) + 2\rho\cos\theta \cdot \vec{e}_n \right]$$

Explanation for the variables:

Φ = solar flux
c = speed of light
} Constants

A = surface area of plate
α = absorptivity of plate
δ = diffuse reflectivity of plate
ρ = specular reflectivity of plate
$\vec{e}_n$ = unit vector normal to plate
} Macromodel definition $\alpha + \delta + \rho = 1$

$\vec{e}_n$ = unit vector normal to plate
$\vec{e}_{\odot}$ = unit vector towards radiation source
θ = angle between $\vec{e}_{\odot}$ and $\vec{e}_n$
} Attitude geometry

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Example for Galileo

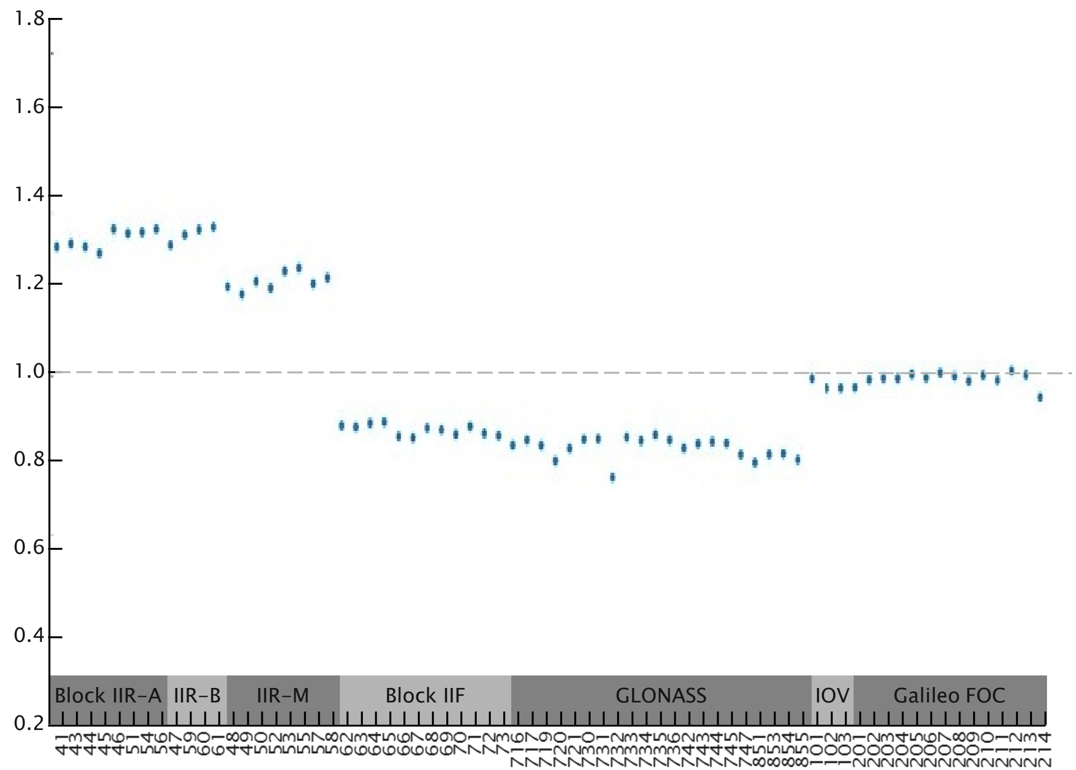
[https://www.esa.int/spaceinimages/Images/2014/07/Galileo_satellite]

- Satellite geometry and optical properties as provided by GSA
- Front side of solar panel has two different “materials”
- Using eqn. (1) or (2) resulted in different scaling factors of about 10%
  -> eqn. (2) is correct
  -> parts of the panel are not used?

Plate	Mod	Area (A) [m^2]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	1.320	[+1, 0, 0]	0.000	0.070		−X Material A
2	1	0.440	[−1, 0, 0]	0.000	0.070		+X Material A
3	1	0.880	[−1, 0, 0]	0.730	0.190		+X Material C
4	1	1.244	[0, +1, 0]	0.000	0.070		−Y Material A
5	1	1.539	[0, +1, 0]	0.730	0.190		−Y Material C
6	1	1.129	[0, −1, 0]	0.000	0.070		+Y Material A
7	1	1.654	[0, −1, 0]	0.730	0.190		+Y Material C
8	1	1.053	[0, 0, +1]	0.000	0.070		+Z Material A
9	1	1.969	[0, 0, +1]	0.220	0.210		+Z Material B
10	1	2.077	[0, 0, −1]	0.000	0.070		−Z Material A
11	1	0.959	[0, 0, −1]	0.730	0.190		−Z Material C
12	0	7.760	[+1, 0, 0]	0.080	0.000	+SUN: [0,+1, 0]	Solar Panels Material E
13	?	3.060	[+1, 0, 0]	0.100	0.000	+SUN: [0,+1, 0]	Solar Panels Material D
14	0	10.820	[−1, 0, 0]	0.196	0.034	−SUN: [0,+1, 0]	Solar Panels back

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Yearly Scale Factors: Monoscale

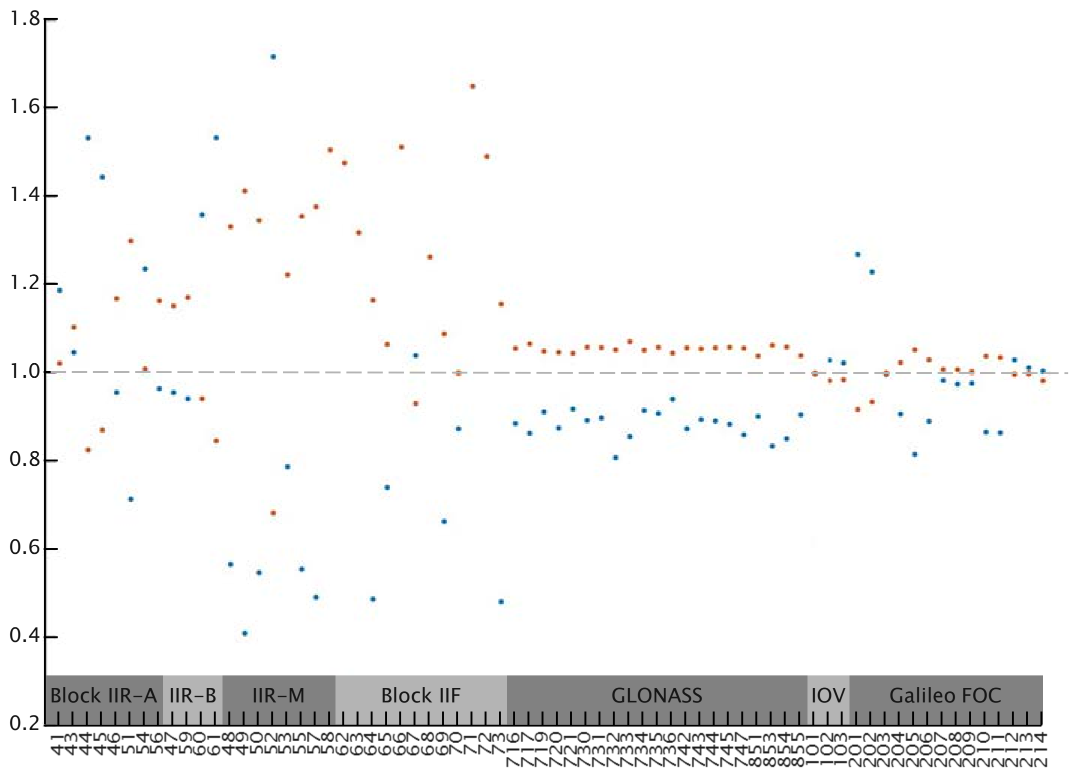


Monoscale:
(one factor per satellite)

The scale factors show clearly the different types of satellites.

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.**
Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Yearly Scale Factors: Smartscale-2



Smartscale-2:
(two factor per satellite: solar panel and body)

GLONASS & Galileo: stable scale factors for all satellites in same block -> close to 1

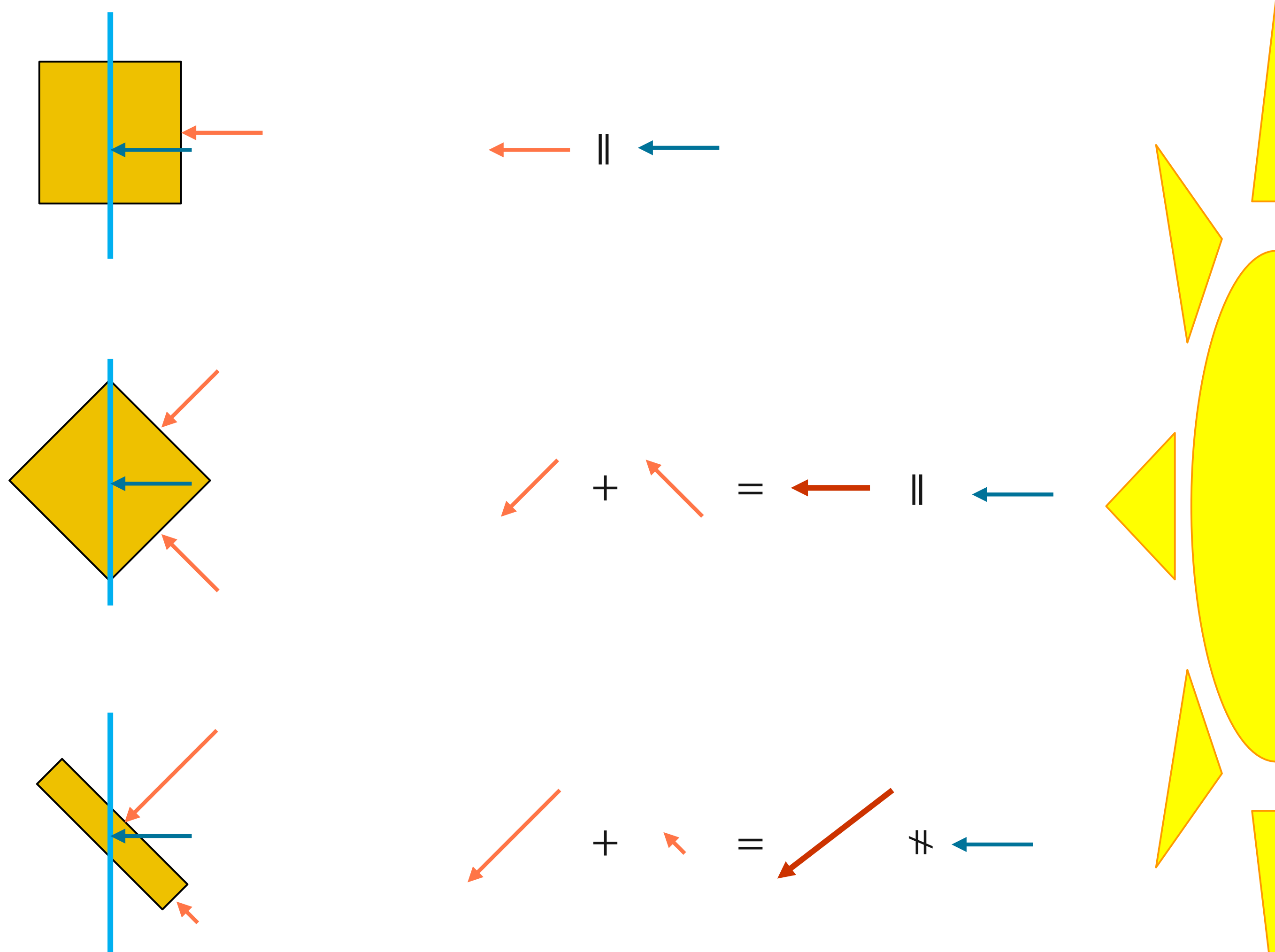
GPS: more variation between satellites in same block -> farther away from 1.

L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Monoscale vs. Smartscale/Multiscale

Correlation between scale factors due to:

- Similar optical properties
- Parallel plates
- Attitude geometry
- Parallel resultant force

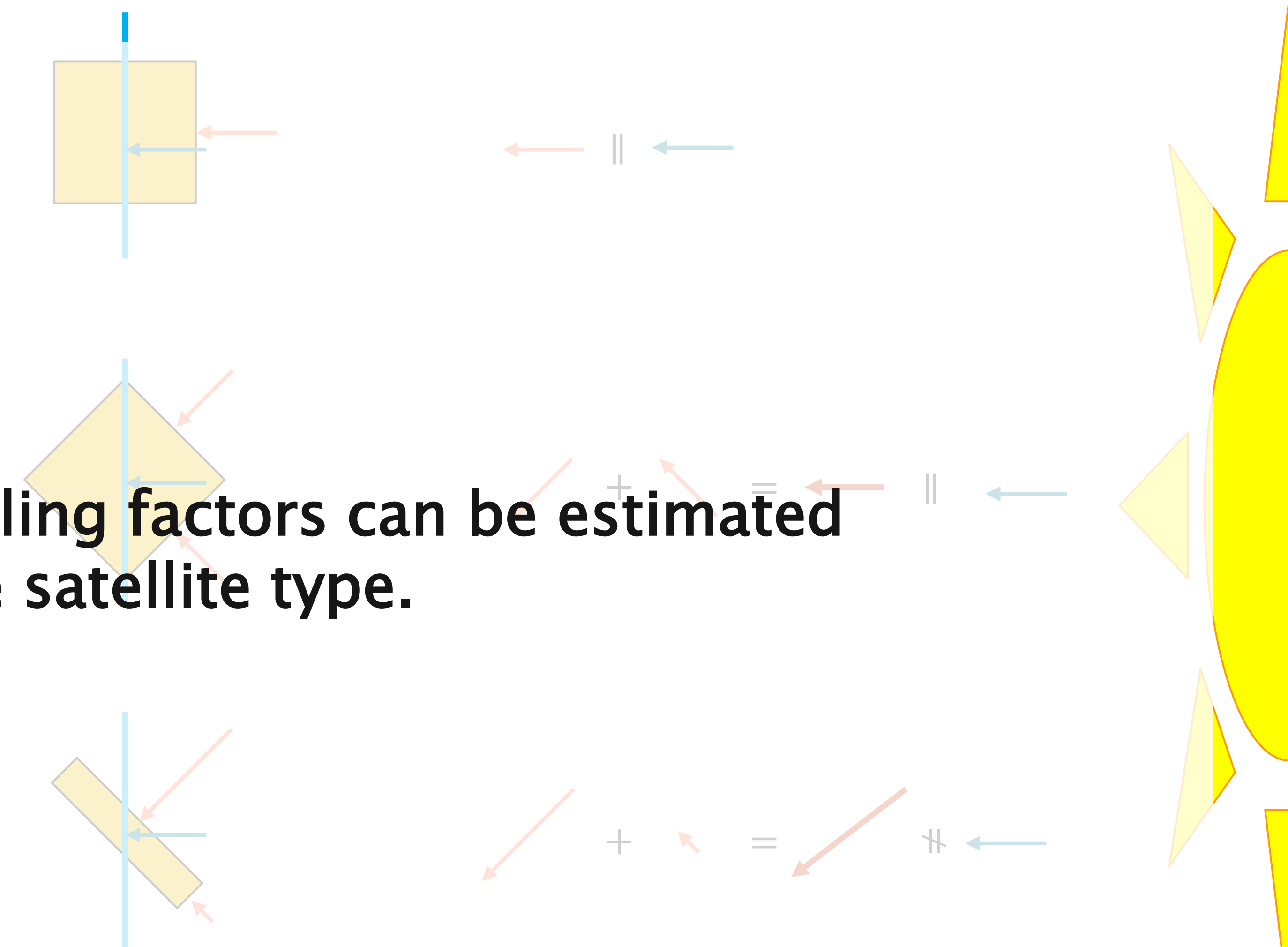


L. McNair, A.Villiger, R. Dach, A. Jäggi: **Validation of boxwing models for GNSS satellites.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Monoscale vs. Smartscale/Multiscale

Correlation between scale factors due to:

- Similar optical properties
- Parallel plates
- Attitude geometry
- Parallel resultant force



Conclusion:

How many scaling factors can be estimated depend on the satellite type.

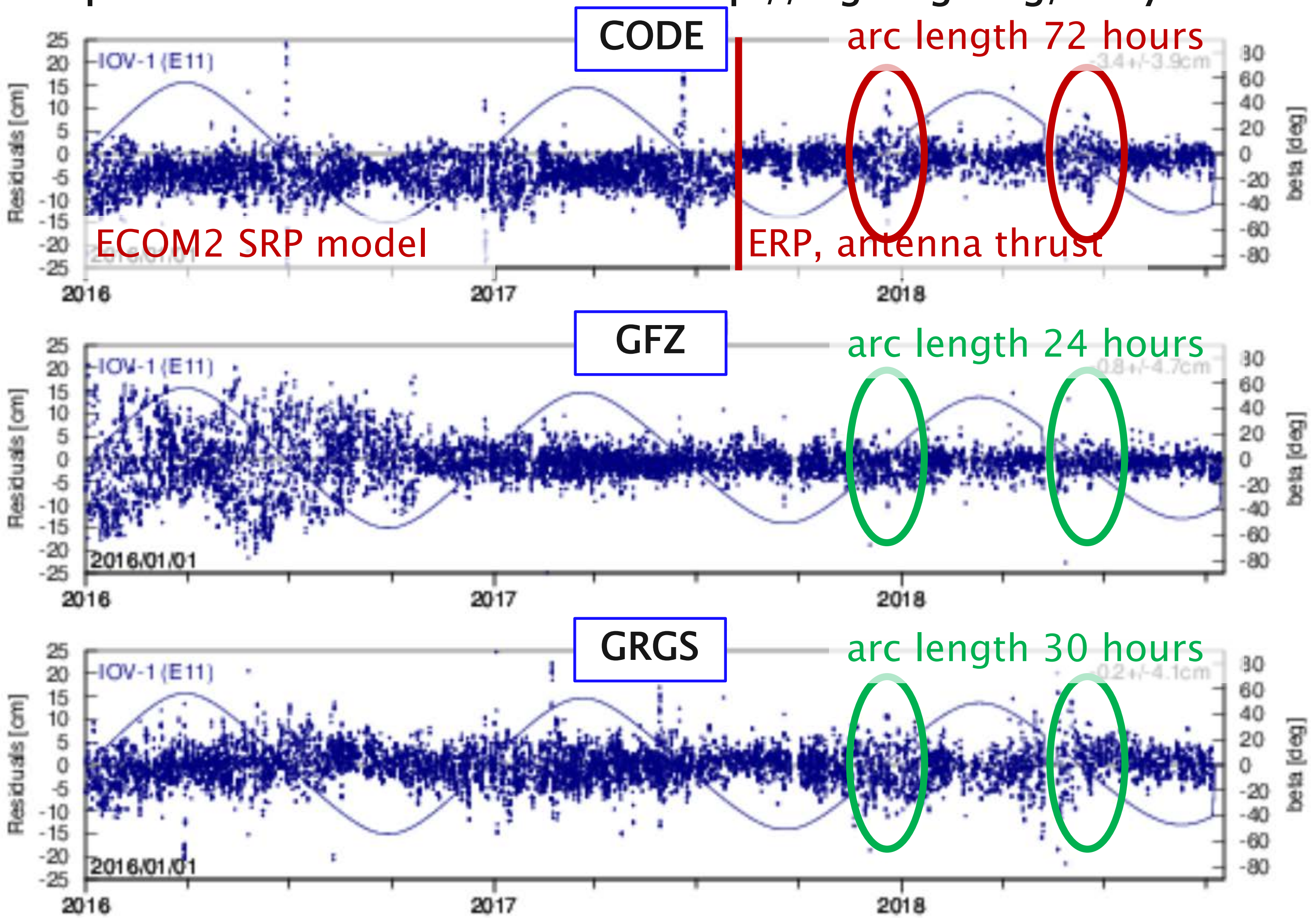
L. McNair, A.Villiger, R. Dach, A. Jäggi: Validation of boxwing models for GNSS satellites. Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orbit modelling during eclipse

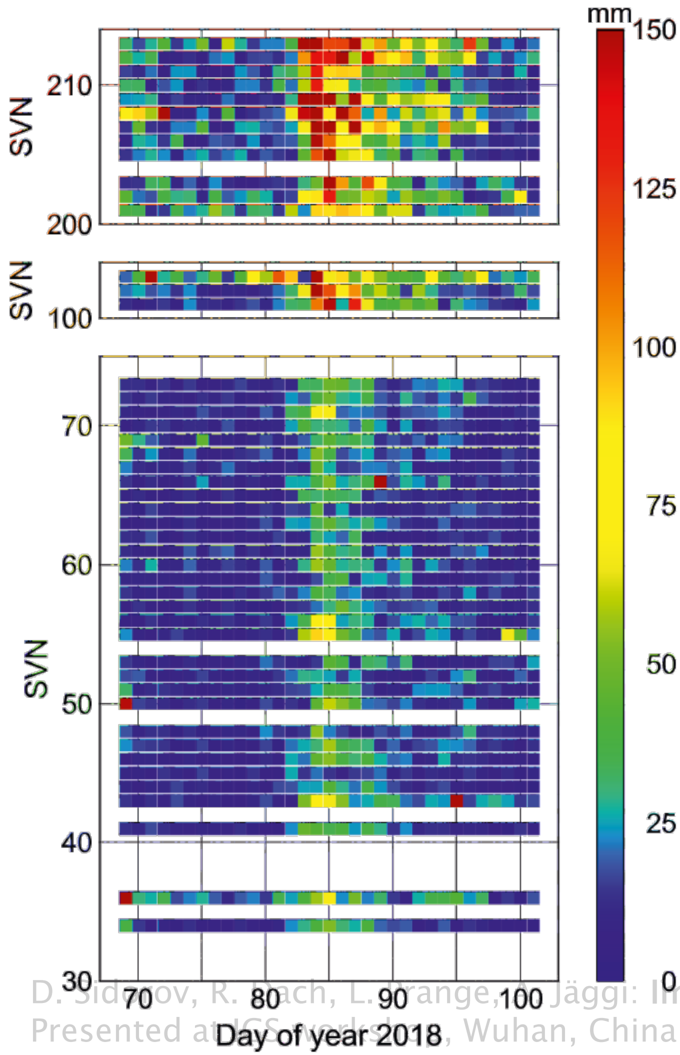
D. Sidorov, R. Dach, L. Prange, A. Jäggi: **Improved orbit modelling of Galileo satellites during eclipse seasons.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

SLR residuals for SVN 101

Comparison of MGEX solutions from http://mgex.igs.org/analysis



Orbit misclosures at midnight



GPS: SVNs: 34–73

Galileo IOV: SVNs: 101–103

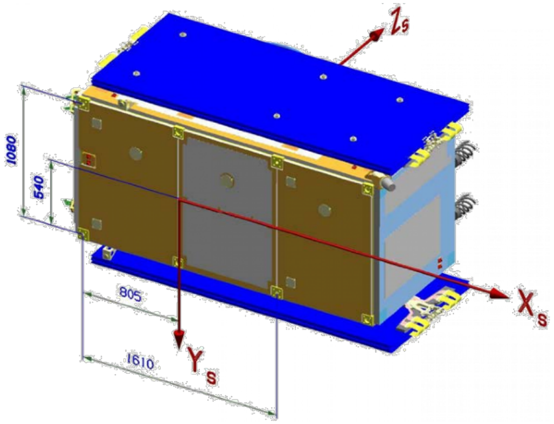
Galileo FOC: SVNs: 201–213

D. Sidorov, R. Dach, L. Prange, A. Jäggi: Improved orbit modelling of Galileo satellites during eclipse seasons. Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Design of Galileo satellites

IOV

FOC

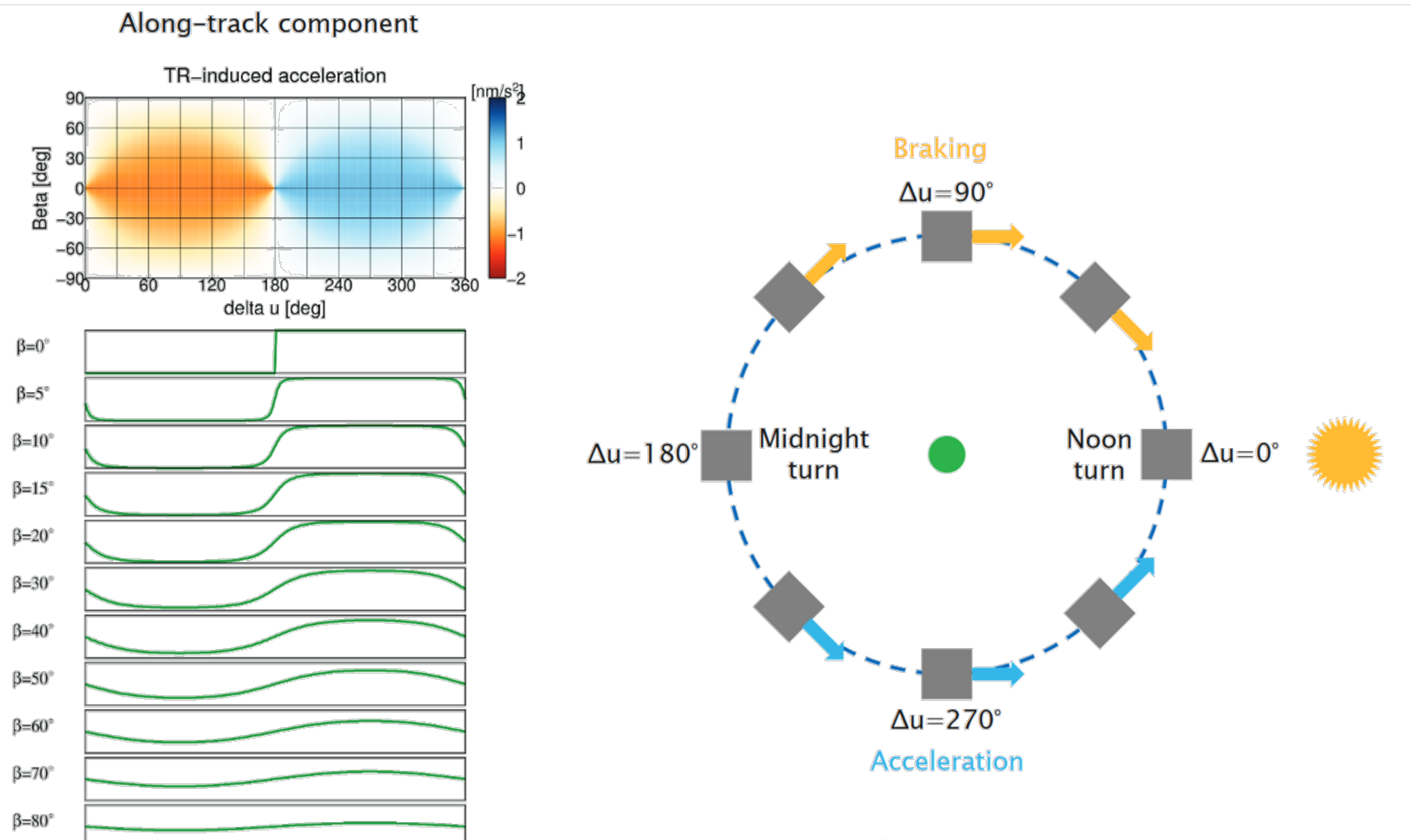


Galileo satellites (Galileo Satellite Metadata, URL: https://www.gsceuropa.eu).

Radiators are installed on
- IOV satellites: +X, +Y, −Y
- FOC satellites: +X, +Y, −Y and −Z

D. Sidorov, R. Dach, L. Prange, A. Jäggi: **Improved orbit modelling of Galileo satellites during eclipse seasons.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Expected effect of the +X radiator



D. Sidorov, R. Dach, L. Prange, A. Jäggi: Improved orbit modelling of Galileo satellites during eclipse seasons. Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

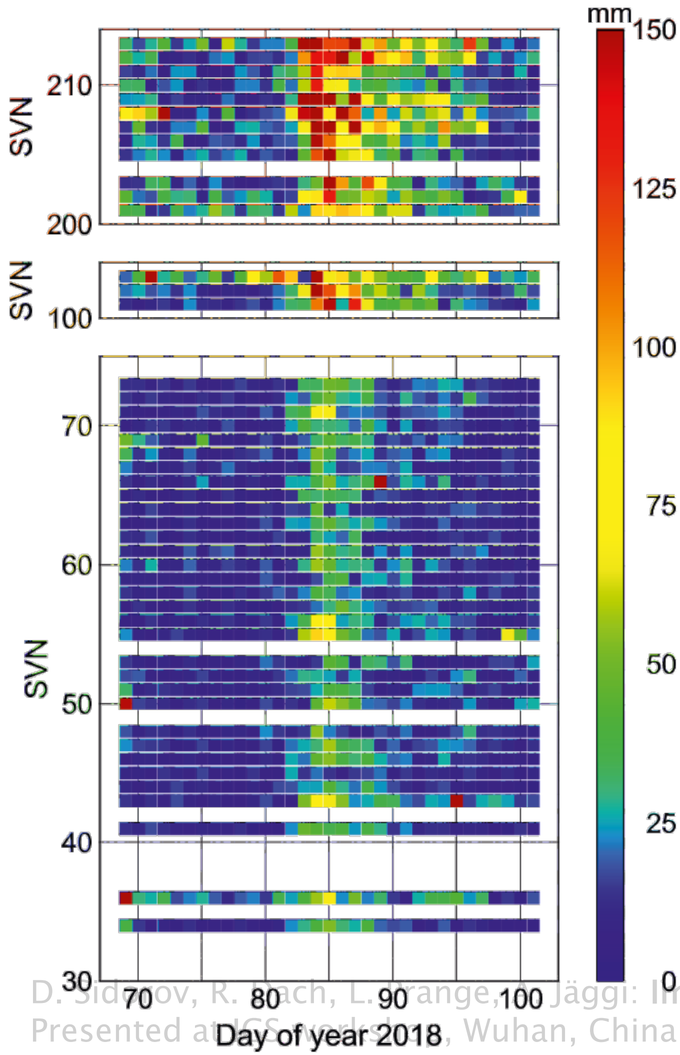
Extending the ECOM2 orbit model

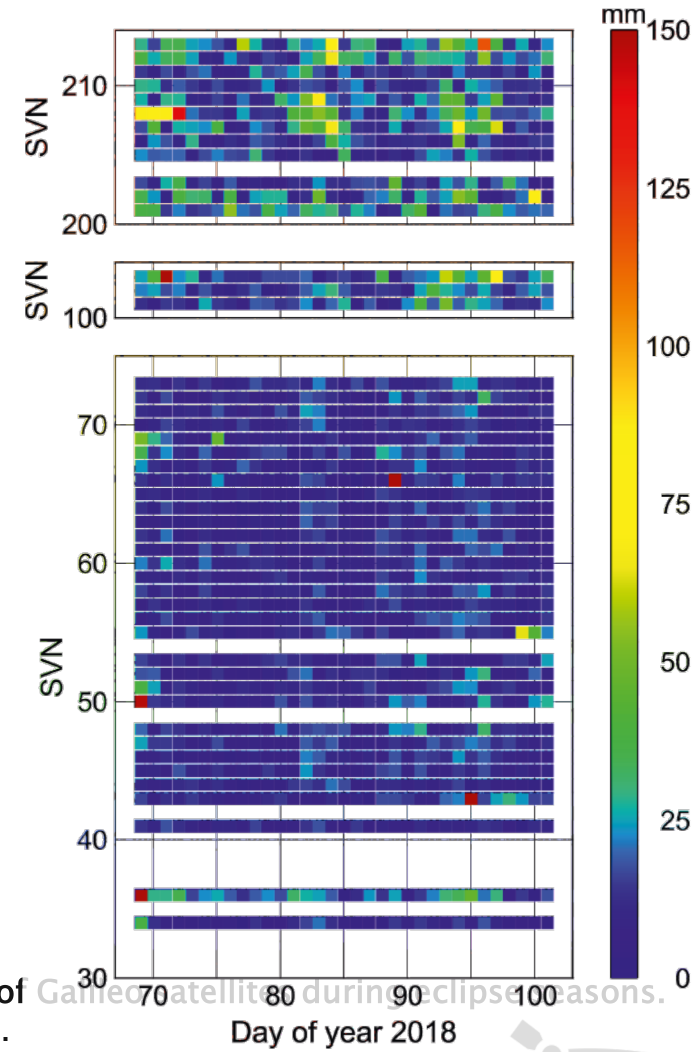
To be accounted by ECOM2:

- for low β<12deg angles requires a once-per-rev sine term in D
- for high β angles a constant term in D is sufficient.

- This additional empirical parameter shall also be active during eclipse season.
- Also the Y-bias parameter is kept active during eclipse to compensate for imbalanced thermal radiation between +Y and -Y radiators.

Orbit misclosures at midnight



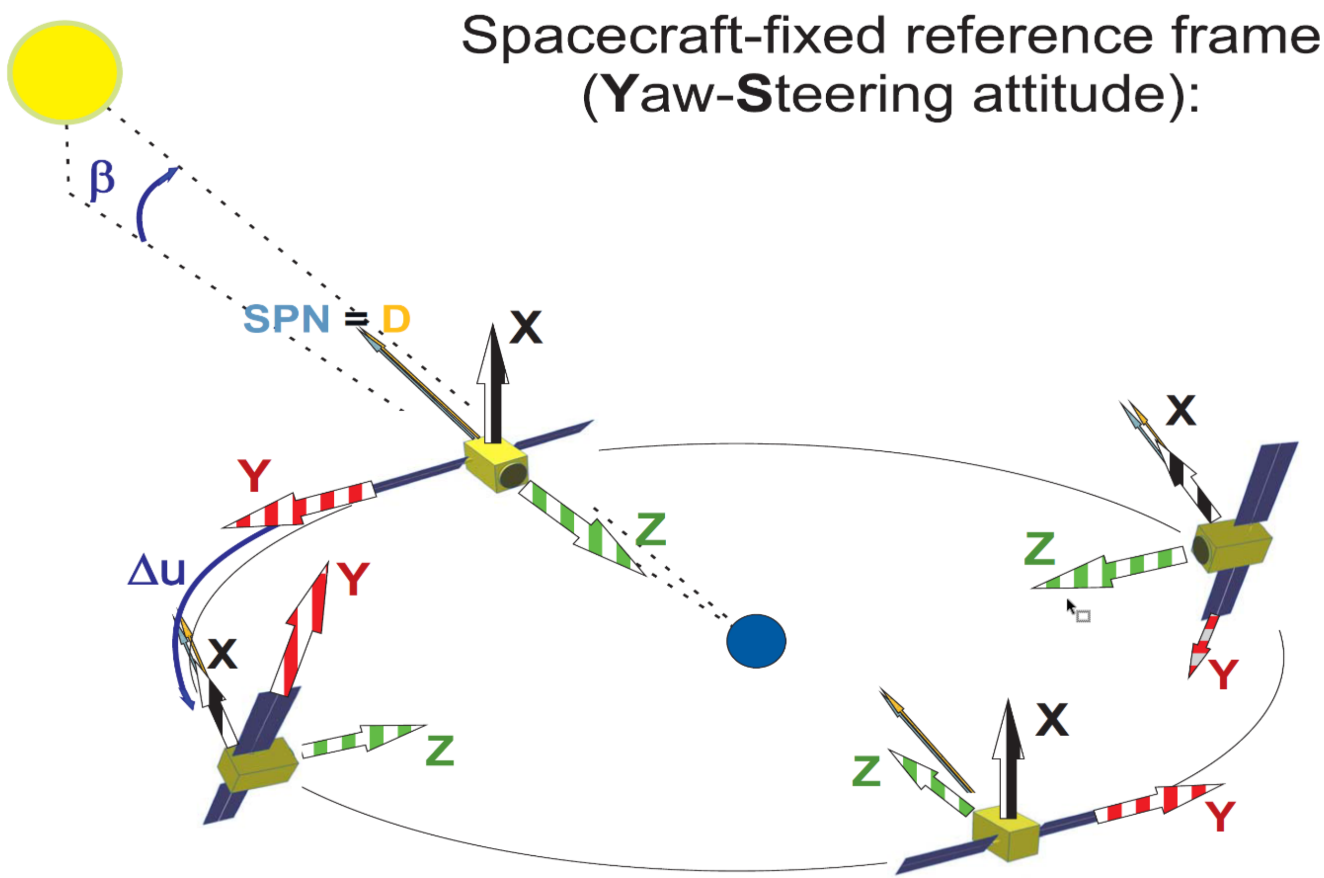


D. Sidorov, R. Dach, L. Prange, A. Jäggi: Improved orbit modelling of Galileo satellites during eclipse seasons. Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Advancing ECOM for satellite in orbit normal mode

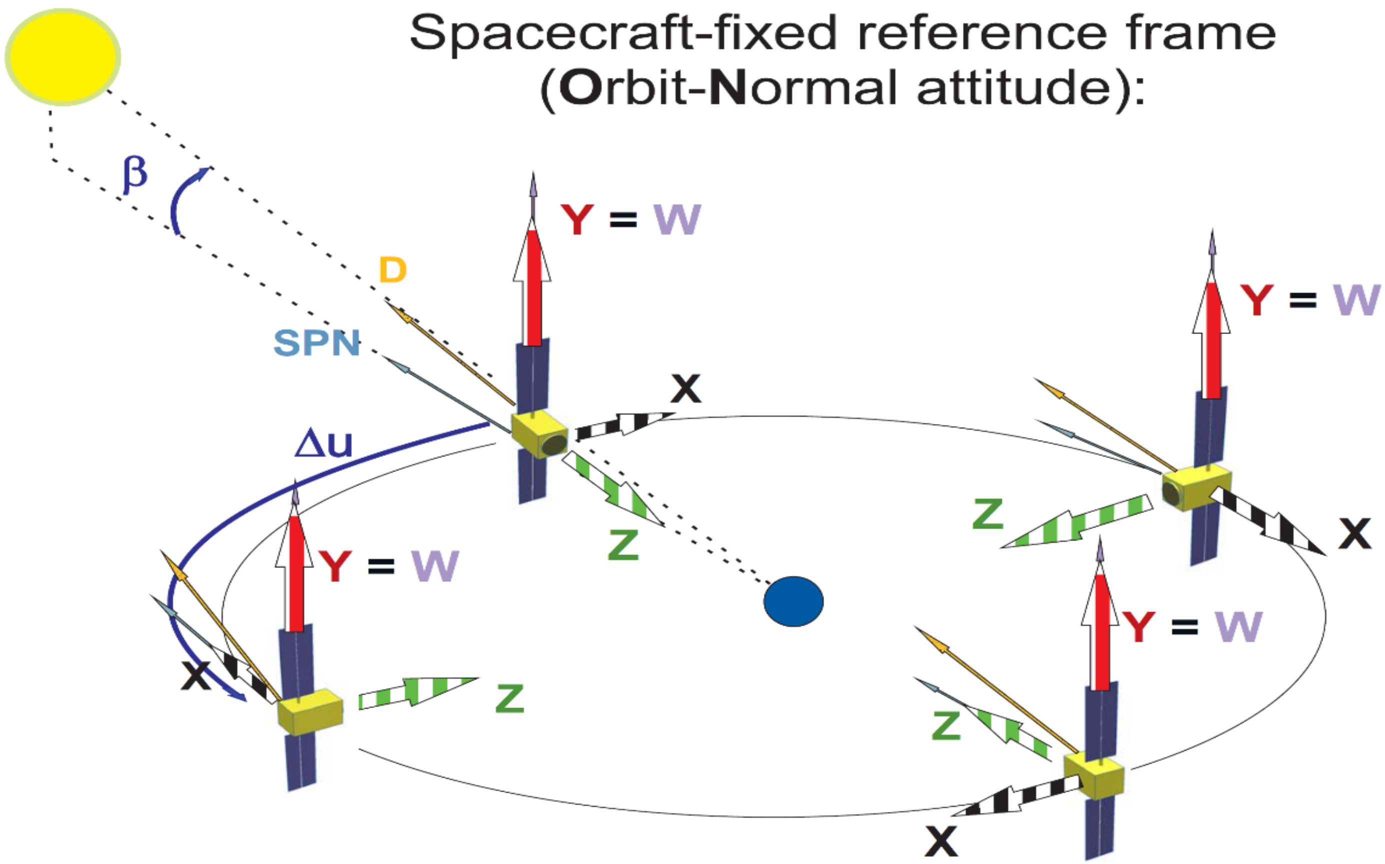
L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orientation of the spacescraft



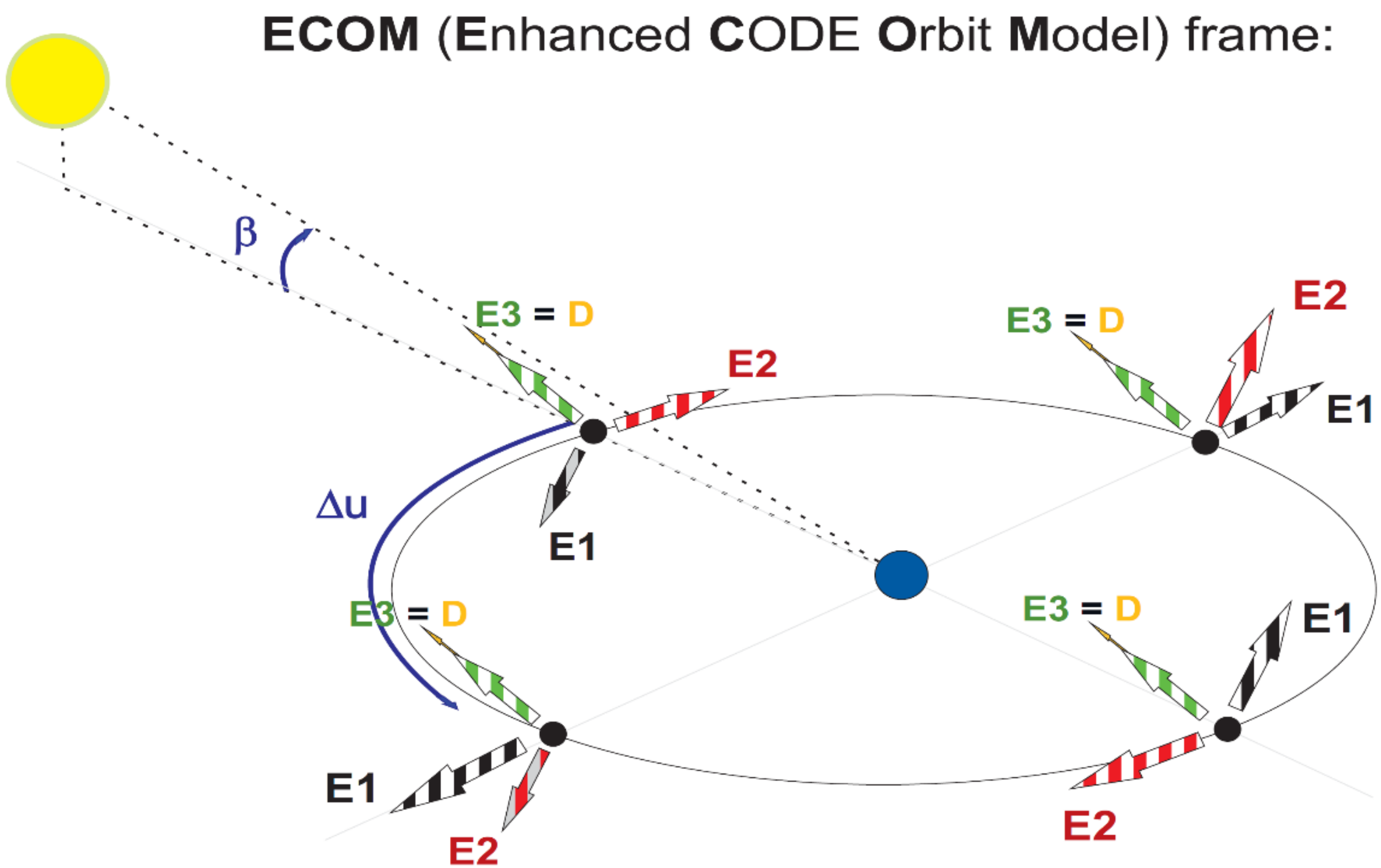
L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orientation of the spacescraft



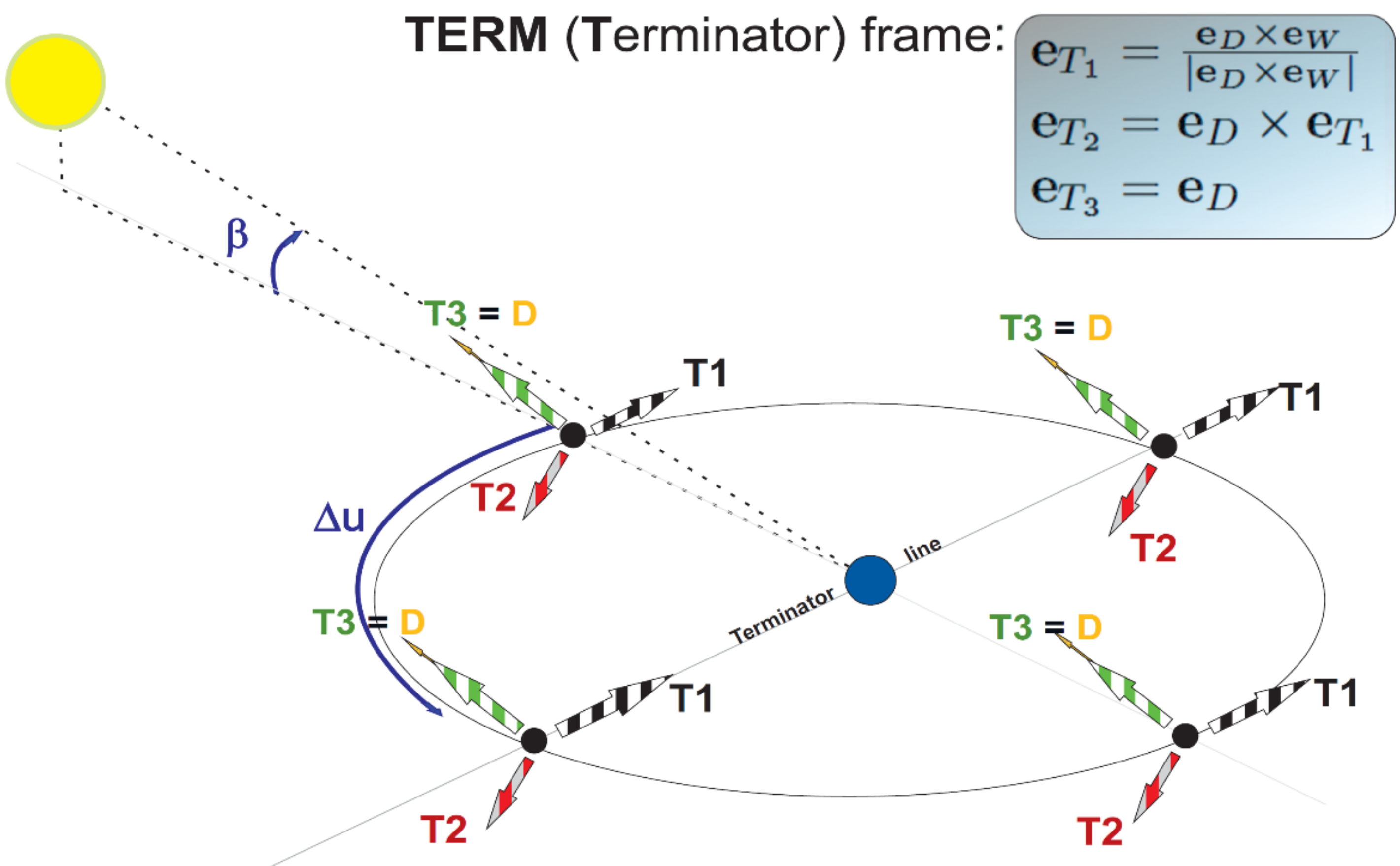
L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Orientation of the coordinate system



L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Orientation of the coordinate system



L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

ECOM updated for orbit normal mode

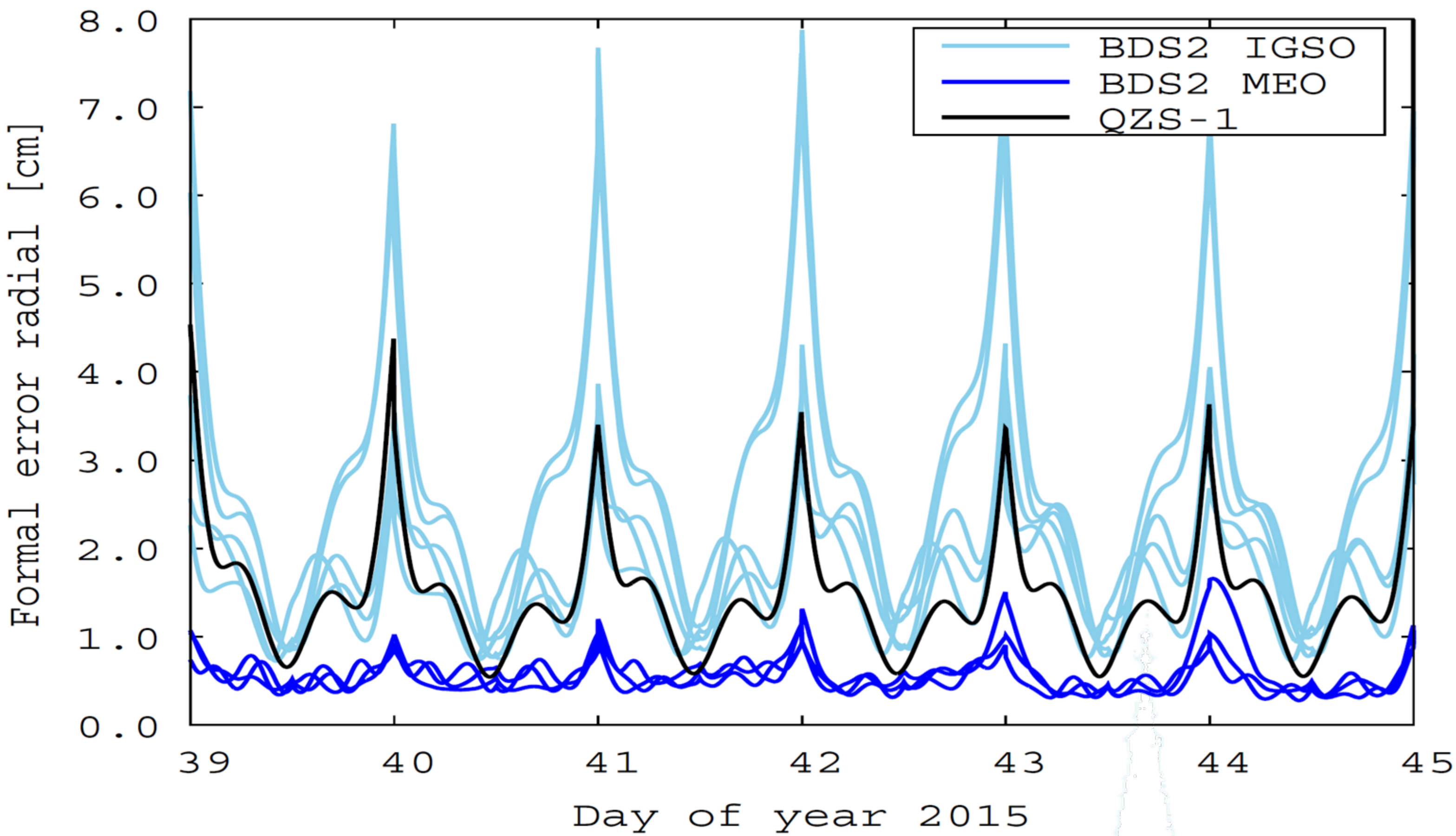
In the terminator-based coordinate system various constant and periodic terms are estimated instead:

- **QZSS-1**: switches at abs(β)<20°
  a 9 parameter model is most efficient

- **BDS-2**: MEO/IGSO switch at abs(β)<4°
  MEO: a 9 parameter model is most efficient
  IGSO: a 2 parameter model is sufficient
  (possibly limited because of the coverage with tracking stations)

L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. - 02 Nov. 2018.

Formal error for radial orbit component



The formal error justify the weak coverage with observations for BDS-IGSO satellites (reason for reduced set of orbit parameters).

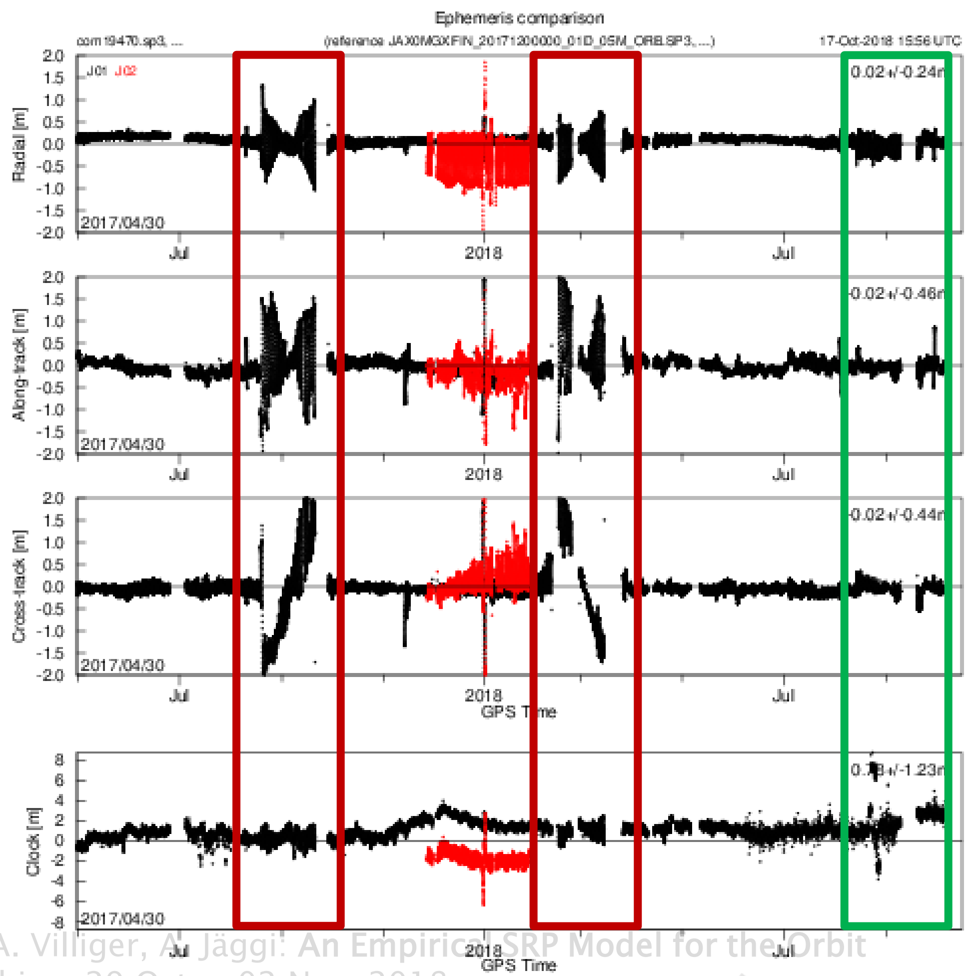
ECOM updated for orbit normal mode

Comparison between CODE-MGEX and JAXA solution for QZSS-satellite(s)

(from http://mgex.igs.org/analysis)

- **ECOM2 orbit model**
  (classical parameters designed for yaw-steering mode)

- **ECOM-TB orbit model**
  (parameters in the terminator-based coordinate system designed for orbit normal mode)



L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

ECOM updated for orbit normal mode

RMS from SLR residuals (IQR):

	BDS2-MEO	BDS2-IGSO	QZSS-1
Old model	20.5 cm	21.0 cm	62.0 cm
New model	12.2 cm	12.2 cm	15.2 cm
Improvement	40.5 %	41.9%	75.5%

Median of a linear fit of the satellite clock corrections:

	BDS2-MEO	BDS2-IGSO	QZSS-1
Old model	1.72 ns	1.61 ns	1.43 ns
New model	0.72 ns	0.69 ns	0.35 ns
Improvement	58.1%	57.1%	75.5%

L. Prange, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Villiger, A. Jäggi: **An Empirical SRP Model for the Orbit Normal Mode.** Presented at IGS workshop, Wuhan, China, 29 Oct. – 02 Nov. 2018.

Summary

Multi-GNSS: more satellites – more challenges for orbit determination

These three examples shall demonstrate

- challenge accepted by CODE and other groups developing GNSS satellite orbit models,
- step by step a progress is made to get the models for the new satellites on the level of GPS orbits,
- a support by the system providers by disclosing information on the satellites is very helpful.

THANK YOU
for your attention

Publications of the satellite geodesy research group:

http://www.bernese.unibe.ch/publist